DISCOVERY ON THE FRONTIERS OF SPACE: EXPLORING NASA'S SCIENCE MISSION

HEARING

BEFORE THE

SUBCOMMITTEE ON SPACE AND AERONAUTICS

OF THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

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C O N T E N T S

June 11, 2019

Appendix II: Additional Material for the Record

DISCOVERY ON THE FRONTIERS OF SPACE: EXPLORING NASA'S SCIENCE MISSION

TUESDAY, JUNE 11, 2019

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON SPACE AND AERONAUTICS,
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Subcommittee met, pursuant to notice, at 10:01 a.m., in room 2318 of the Rayburn House Office Building, Hon. Kendra Horn [Chairwoman of the Subcommittee] presiding.

SUBCOMMITTEE ON SPACE AND AERONAUTICS
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

HEARING CHARTER

Discovery on the Frontiers of Space: Exploring NASA's Science Mission

Tuesday, June 11, 2019
10:00 a.m.
2318 Rayburn House Office Building

PURPOSE

The purpose of the hearing is to review the National Aeronautics and Space Administration's activities and plans for its Earth and space science programs, including the Earth Science, Planetary Science, Astrophysics, and Heliophysics divisions of the Science Mission Directorate, and associated issues.

WITNESSES

- **Dr. Thomas H. Zurbuchen,** Associate Administrator, Science Mission Directorate, National Aeronautics and Space Administration
- **Dr. Chelle Gentemann,** Senior Scientist, Earth and Space Research; Co-chair, Committee on Earth Science and Applications from Space, Space Studies Board, National Academies of Sciences, Engineering, and Medicine
- **Dr. David Spergel,** Charles A. Young Professor of Astronomy, Princeton University; Director, Center for Computational Astrophysics at the Flatiron Institute; Former Chair, Space Studies Board, National Academies of Sciences, Engineering, and Medicine
- **Dr. Mark Sykes,** Chief Executive Officer and Director, Planetary Science Institute

OVERARCHING QUESTIONS

- *What are the emerging science questions in astrophysics, planetary science, heliophysics, and Earth science, and what, if any, developments are key to enabling progress in answering them?*
- *What is the status of NASA's implementation of the priorities put forth by the scientific community through the National Academies' decadal surveys?*
- *What are the most significant challenges and opportunities for the future of space and Earth science research?*
- *What is the status of NASA's science research grants program and what needs to be done to ensure its continued productivity?*

- *What questions and issues need to be considered regarding the relationships among science, human exploration, and commercial space activities?*

BACKGROUND

Scientific research has been part of the NASA mission since the agency's founding. The National Aeronautics and Space Act of 1958 includes among the eight objectives of the nation's aeronautical and space activities: "The expansion of human knowledge of phenomena in the atmosphere and space."[1] The NASA Transition Act of 2017 amended the list to include another science-related objective: "The search for life's origin, evolution, distribution, and future in the universe."[2] NASA's Science Mission Directorate (SMD) is the primary home of NASA's science efforts, although programs in the Human Exploration and Operations Mission Directorate (including the Division of Space Life and Physical Science Research and Applications) and the Space Technology Mission Directorate involve science-related activities. NASA's SMD comprises four scientific divisions:

- Earth Science, which seeks to advance knowledge of Earth as a system to meet the challenges of environmental change and to improve life on our planet.
- Planetary Science, which seeks to ascertain the content, origin, and evolution of the Solar System and potential for life elsewhere.
- Astrophysics, which seeks to discover how the Universe works, explore how it began and evolved, and search for life on planets around other stars.
- Heliophysics, which seeks to understand the Sun and its interactions with Earth, the Solar system, and the interstellar medium, including space weather.

NASA's Science Mission Directorate as Proposed in the FY 2020 NASA Budget Request

The NASA Fiscal Year (FY) 2020 budget request for SMD, as detailed in the table below,[3] proposes a total of $6.3 billion, a 9% cut from the FY 2019 enacted appropriation. In addition to the budget lines for the four divisions listed above, the James Webb Space Telescope (JWST), an astrophysics mission in development, is book-kept in a separate budget line within SMD.

Budget Authority (in $ millions)	Actual FY 2018	Enacted FY 2019	Request FY 2020	FY 2021	FY 2022	FY 2023	FY 2024
Earth Science	1921.0	--	1779.8	1785.6	1779.7	1666.5	1674.6
Planetary Science	2217.9	--	2622.1	2577.3	2629.4	2402.4	2350.9
Astrophysics	850.4	--	844.8	902.4	965.2	913.5	907.7
James Webb Space Telescope	533.7	375.1	352.6	415.1	175.4	172.0	172.0
Heliophysics	688.5	--	704.5	638.6	769.3	692.0	709.8
Total Budget	**6211.5**	**6905.7**	**6303.7**	**6319.0**	**6319.0**	**5846.5**	**5815.0**
Change from FY 2019			-602.0				
Percentage change from FY 2019			-8.7%				

[1] U. S. Code 51.20102(d)(1)
[2] U. S. Code 51.20102(d)(10)
[3] Table from page SCMD-4, NASA FY2020 Budget Request, Congressional Justification

The four science divisions manage diverse portfolios of research, missions, and technology development. Competitively-selected grants in research and analysis support approximately 10,000 (in 2018) students, postdoctoral fellows, and scientists both at NASA centers and at institutions around the country.[4] SMD operates a fleet of more than 80 spacecraft from low Earth orbit (LEO) to beyond the edge of the Solar System that is a mix of small, medium, and large ("flagship") missions, including competitively-selected principal investigator-led (PI) missions and NASA-led large-scale, "flagship" missions. High-altitude balloons, sounding rockets, and CubeSats and small satellites additionally support science, technology demonstrations, and student projects under SMD. In addition, across the divisions, SMD invests in early-stage technology development to enable potential future missions and SMD's Science Activation program supports competitively-selected teams to connect NASA science experts and content to learners. As stated in the FY 2020 Congressional Budget Justification document, NASA "*uses the recommendations of the National Academies' decadal surveys as an important input in planning and prioritizing the future of its science programs.*"

NASA Programs and the National Academies of Sciences, Engineering, and Medicine's Decadal Surveys

NASA contracts with the National Academies of Sciences, Engineering, and Medicine[5] to carry out "decadal surveys," community consensus reports that prioritize the most compelling science questions for the next decade and recommend a program to best address them and optimize scientific return on federal investment.[6] The National Academies published the first decadal survey in astronomy in 1964[7] and has published a new survey approximately every ten years since. The National Academies went on to issue the first decadal surveys in planetary science and solar and space physics in 2003 and Earth science in 2007.[8] NASA is the primary sponsor of these decadal surveys; however, other relevant federal agencies, such as the National Science Foundation (NSF), Department of Energy (DOE), National Oceanic and Atmospheric Administration (NOAA), and U.S. Geological Survey (USGS), may be co-sponsors. NASA is required[9] to take into account the decadal surveys when submitting the President's annual budget request to Congress. Decadal surveys and mid-decade assessments ("midterms") in the four disciplines are now carried out regularly on a staggered schedule. A consistent theme of the decadal surveys is the importance of "balance," which includes maintaining not only a diverse portfolio of small, medium, and large missions, but also a strong research grant program in addition to missions. In addition, decadal surveys may also consider budget scenarios for the next decade, as well as technology development, research, infrastructure, and workforce.

[4] https://science.nasa.gov/about-us
[5] The National Academy of Sciences was established in 1863 by an Act of Congress signed into law by President Lincoln as an independent, nongovernmental institution to advise the government. The Academies of Engineering and Medicine were established later under the charter of the National Academy of Sciences.
[6] Section 20305(a), Title 51, U.S. Code
[7] National Academy of Sciences. 1964. *Ground-based Astronomy: A Ten-Year Program.* Washington, DC: The National Academies Press. https://doi.org/10.17226/13212.
[8] Alexander, Joseph K. *Science Advice to NASA: Conflict, Consensus, Partnership, Leadership.* 2017. NASA Office of Communications, NASA History Division. Monographs in Aerospace History, No. 57. https://www.nasa.gov/connect/ebooks/science_advice_to_nasa_detail.html.
[9] Section 18384, Title 42, U.S. Code

Astrophysics

The SMD Astrophysics Division supports research investigations with grants and a high-altitude balloon project. The Astrophysics Cosmic Origins program studies the nature and evolution of stars and galaxies and operates two flagship missions, the Hubble Space Telescope (HST) and the Stratospheric Observatory for Infrared Astronomy (SOFIA). The Physics of the Cosmos program enables study of cosmology and fundamental physics and operates the flagship Chandra X-ray Observatory. The Exoplanet Exploration program enables the search for and characterization of planets outside of our solar system and manages the development of the flagship Wide Field Infrared Survey Telescope (WFIRST) mission, which will have the same sensitivity as HST, but a new, cutting-edge suite of instruments and a field of view 100 times larger. It was the highest priority large mission of the 2010 decadal survey. Astrophysics Explorers are competitively selected small and medium class missions.

The James Webb Space Telescope (JWST), which was the highest large space project priority of the 2000 decadal survey,[10] is managed separately from the Astrophysics division. JWST will observe the universe in infrared light to study stars hidden by dust, the atmospheres of planets around other stars, and the first light from the earliest galaxies formed after the Big Bang.

The 2010 decadal survey, *New Worlds, New Horizons in Astronomy and Astrophysics*,[11] was the sixth for the astronomy and astrophysics community. The decadal survey identified three science objectives:

- Cosmic Dawn: Searching for the First Stars, Galaxies, and Black Holes
- New Worlds: Seeking Nearby, Habitable Planets
- Physics of the Universe: Understanding Scientific Principles

Astrophysics Large-Scale Priorities	
Program	*Notes from Decadal Recommendation*
1. Wide Field Infrared Survey Telescope (WFIRST)	Partnership with DOE
2. Explorer Program Augmentation	Support the selection of two Medium-Class Explorers (MIDEX), two Small Explorers (SMEX), and four Missions of Opportunity (MO)
3. Laser Interferometer Space Antenna (LISA)	Partnership with European Space Agency (ESA)
4. International X-Ray Observatory (IXO)	Partnership with ESA and Japanese Aerospace Exploration Agency (JAXA)
Astrophysics Medium-Scale Priorities	
1. New Worlds Technology Development Program	Technology development for a potential planet-imaging mission beyond 2020
2. Inflation Probe Technology Development Program	Technology development for a potential cosmic microwave background and/or inflation mission beyond 2020

[10] National Research Council. 2001. *Astronomy and Astrophysics in the New Millennium*. Washington, DC: The National Academies Press. https://doi.org/10.17226/9839.
[11] National Research Council. 2010. *New Worlds, New Horizons in Astronomy and Astrophysics*. Washington, DC: The National Academies Press. https://doi.org/10.17226/12951.

The decadal survey in astronomy and astrophysics for the 2020-2030 decade is in progress.[12]

Planetary Science

The Planetary Science Division supports research investigations through grants, curation of samples and materials collected from science missions, and management of the Planetary Data System (PDS) archive. The Division supports PI-led missions in the Discovery (small-class) and New Frontiers (medium-class) mission lines. Planetary Science is currently developing two large-scale flagship missions: the Mars 2020 Rover, which will investigate the Red Planet's past and present conditions for life and collect rock and soil samples for future return to Earth, and Europa Clipper, which will perform a detailed study of Jupiter's icy moon, Europa, which harbors a liquid ocean below its ice shell and thus a potential site for life in the Solar System. In addition, the Division is NASA's home for Planetary Defense, including observations to identify and characterize Near Earth Objects (NEOs) and testing of mitigation technology for hazardous asteroids. The Planetary Science Division manages the acquisition of radioisotope power materials, in partnership with the Department of Energy, that is needed for missions for which solar power is not feasible or sufficient.

The 2011 *Visions and Voyages for Planetary Science in the Decade 2013-2022*[13] was the second decadal survey in the field. The committee identified ten primary science questions of the next decade under three broad, crosscutting themes:

- Building new worlds—understanding solar system beginnings,
- Planetary habitats—searching for the requirements of life, and
- Workings of solar systems—revealing planetary processes through time.

The survey prioritized three large flagship space missions for the decade and also recommended one medium-scale program of two New Frontiers missions, competitively selected out of a list of candidate missions.

Planetary Science Large-Scale Priorities	
Program	*Notes from Decadal Recommendation*
1. Mars Astrobiology Explorer-Cacher (MAX-C) descope	Partnership with ESA Should be flown only if it can be conducted for a cost to NASA of no more than $2.5 billion (FY 2015 dollars)
2. Jupiter Europa Orbiter (JEO) descope	Should be flown only if changes to both the mission and the NASA planetary budget make it affordable without eliminating any other recommended missions
3. Uranus Orbiter and Probe	Should be initiated in the decade even if both MAX-C and JEO take place
Planetary Science Medium-Scale Priority	
1. New Frontiers	New Frontiers-4 candidate missions: Comet Surface Sample Return; Lunar South Pole-Aitken Basin Sample Return; Saturn Probe; Trojan Tour and Rendezvous; Venus In-Situ Explorer

[12] https://sites.nationalacademies.org/DEPS/astro2020

[13] National Research Council. 2011. *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13117.

	New Frontiers-5 candidate missions: All of the above not selected in New Frontiers-4, and Io Observer, Lunar Geophysical Network

Heliophysics

The Heliophysics Division supports research investigations through grants, CubeSats, and a sounding rocket program. The Living With a Star (LWS) program seeks to understand aspects of the Sun-Earth system that affect life and society and includes the study of space weather, including solar phenomena like coronal mass ejections and solar wind interactions with the Earth like geomagnetic storms, which can impact Earth's power grid, space-based technologies like communications and navigation systems, and the harmful radiation environment for humans in space. The Division's Solar Terrestrial Probe (STP) missions focus on the fundamental physical processes of the space environment; and an Explorer program for competed small and medium missions. The Heliophysics Division operates the Parker Solar Probe, which is making record-breaking close approaches to the Sun to understand its atmosphere, or corona. Heliophysics missions in development include the Interstellar Mapping Probe (IMAP), the next STP mission, and U.S. contributions to the ESA-led Solar Orbiter Collaboration mission.

The 2013 *Solar and Space Physics: A Science for a Technical Society*[14] was the second decadal survey for Heliophysics. The survey's four key science goals for the decade, "*considered of equal priority*," were:

- Determine the origins of the Sun's activity and predict the variations in the space environment.
- Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.
- Determine the interaction of the sun with the solar system and the interstellar medium.
- Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

Heliophysics Decadal *Science* Priorities	
Program	*Notes from Decadal Recommendation*
1. Implement the Diversify, Realize, Integrate, Venture, Educate (DRIVE) Initiative	Includes small satellites, science centers and grant programs, and instrument development
2. Accelerate and expand the Heliophysics Explorer Program	Enable Medium Explorer and Mission of Opportunity lines resulting in an increased cadence of one launch every 2-3 years
3. Restructure Solar Terrestrial Probes as a moderate-scale, PI-led line	Implement three mid-scale missions meeting the science targets of the following reference missions (priority order): 1. Interstellar Mapping and Acceleration Probe (IMAP) 2. Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC) 3. Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI)

[14] National Research Council. 2013. Solar and Space Physics: A Science for a Technological Society. Washington, DC: The National Academies Press. https://doi.org/10.17226/13060.

4. Implement a large Living with a Star (LWS) Geospace Dynamics Constellation (GDC)-like mission	

The top priority of the Heliophysics decadal survey—after maintaining the current program—is the DRIVE initiative, a "*new, integrated, multiagency initiative...that will develop more effectively the many experimental and theoretical assets at NASA, NSF, and other agencies.*"

A mid-decade assessment of the progress implementing the decadal survey is currently underway and is expected to be released by the end of 2019.[15]

Earth Science and Applications

NASA's Earth Science Division supports research investigations; directed Earth system science missions; competitively selected, small, space-based and airborne missions; a significant division-wide data systems management effort; advanced technology development; and an applied science program. Operating Earth Science missions include Landsat (in partnership with USGS), the Global Precipitation Measurement mission, and the Soil Moisture Active and Passive Mission. The Division is currently developing the Landsat 9 satellite, which will continue the program's critical role in monitoring global land surface for natural and human-induced change, and the Surface Water and Ocean Topography Mission, which will make the first-ever global survey of Earth's surface water. The Division's Applied Sciences program uses Earth Science data to develop decision-making tools that serve multiple public and private sector users. Examples of applications include wildfire detection data and predictions for use by the U.S. Forest Service and the use of soil moisture data by the U.S. Department of Agriculture.

The 2018 *Thriving On Our Changing Planet: A Decadal Strategy for Earth Observation in Space*[16] was the second decadal survey for Earth science. The survey identified 35 key science and applications questions for the next decade spanning the following six areas:

- Coupling of the water and energy cycles
- Ecosystem change
- Extending and improving weather and air quality forecasts
- Reducing climate uncertainty and informing societal response
- Sea-level rise
- Surface dynamics, geological hazards, and disasters

The 2018 Earth Science decadal survey differs from other surveys in that it "*puts forth a set of priority measurements rather than prescribing specific mission implementations...this approach allows the program implementation to evolve throughout the course of the decade in order to take advantage of new ideas such as constellations of small spacecraft, advances in sensor technology, and better computational techniques.*"[17] The survey paired a ranked list of distinct

[15] http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_174910

[16] National Academies of Sciences, Engineering, and Medicine. 2018. *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24938.

[17] https://www.nap.edu/resource/24938/RH-esas.pdf

program elements with a list of "targeted observables," or priority observations. Ahead of new priorities, the Earth Science decadal survey prioritized completion of the program of record.

Earth Science Decadal Priorities	
Program	*Notes*
2. Designated Observables	A program element for cost-capped, competed or directed, medium- and large-size missions to address observables essential to the overall program: aerosols; clouds, convection, and precipitation; mass change; surface biology and geology; and surface deformation and change.
3. Earth System Explorer	A *new* program element for competitive, cost-capped medium-size instruments and missions targeting: Greenhouse gases, Ice elevation, Ocean surface winds and currents, ozone and trace gases, snow depth and snow water equivalent; and terrestrial ecosystem structure.
4. Incubation	A *new* program element focused on investment for capabilities for priority observations: atmospheric winds, planetary boundary layer, and surface topography and vegetation, with an innovation fund to respond to emerging needs.
5. Earth Venture	Add *new* "Venture-continuity" component to existing Earth Venture program element.

NASA Science Mission Cost and Schedule Performance

The Government Accountability Office (GAO) found in its 2018 agency-wide assessment of NASA's "major projects"—those in development, with projected lifecycle costs of at least $250 million—[18] that the cost and schedule performance of NASA's "*portfolio of major projects continues to deteriorate,*" largely due to challenges with JWST's integration and testing and production challenges with the human exploration program's Space Launch System.

Science and Exploration

NASA introduced in its FY 2019 budget proposal a Lunar Discovery and Exploration budget line within the SMD Planetary Science Division. Included in the budget line is a new program, Commercial Lunar Payload Services (CLPS). Through CLPS, NASA is procuring a service as a means to deliver science, technology, and human exploration payloads to the lunar surface, starting with landers at a cadence of 1-2 launches each year. The first CLPS provider selections were announced last month.[19] Three commercial landing service providers will deliver NASA-provided payloads to the lunar surface by July 2021.

[18] GAO-19-262SP. 2019. "NASA: Assessment of Major Projects." https://www.gao.gov/products/GAO-19-262SP
[19] https://www.nasa.gov/press-release/nasa-selects-first-commercial-moon-landing-services-for-artemis-program

Chairwoman HORN. This hearing will come to order.

Without objection, the Chair is authorized to declare recess at any time.

Good morning, and welcome. I especially want to welcome our witnesses, and thank you very much for being here this morning.

Before we begin our second hearing, I want to say it is truly an honor and a pleasure to Chair this Subcommittee and to note that our investments in space and aeronautics are catalysts for growth, discovery, innovation, and economic growth in America. I'm grateful for the opportunity to work with Ranking Member Babin and all of the Members as we consider the important issues before the Subcommittee.

We began by focusing our first hearing on human space exploration. We have a lot to do, and today we are turning our attention to science. Space science has come a long way in the 60 years since NASA's (National Aeronautics and Space Administration's) founding and James Van Allen's launch of Explorer 1, America's first science satellite, in 1958. While Explorer 1 provided initial glimpses into what could be discovered from vantage points above and beyond the surface of Earth, NASA's science spacecraft have gone on to study our Sun and every planet in the solar system, to look back into the early universe, and to enhance our understanding of our own planet.

Today, NASA's Science Mission Directorate (SMD) represents a $6.9 billion investment that funds space-based and suborbital science missions, ground-based research, data analysis, and technology development. These elements support NASA's programs focused on planetary science, Earth science and applications, astrophysics, and heliophysics—the study of the Sun and its interactions with the Earth and the solar system.

Through these programs, scientists are seeking answers to questions—to fundamental questions: What is dark energy? And how and why is the universe expanding, and at what rate? How have the many chemical and physical processes that shaped the solar system evolved and interacted over time? What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space? What are the origins of the Sun's activity and how can we predict variations in the space environment?

In pursuing answers to these and other questions, NASA's scientific findings increasingly become interwoven into our everyday lives, from decisions to reroute aircraft due to solar activity and space weather, to surveying the skies for potentially harmful near-Earth asteroids, to using ocean color and temperature maps for commercial fishery forecasting, or in using satellite data to assess the impacts of our changing climate, and much more.

Through an organized, science community-led process known as the decadal surveys, NASA's Science Mission Directorate has benefited from a systemic approach to setting priorities that guide NASA's planetary, heliophysics, astrophysics, and Earth science program over 10 years. Not only do the decadal surveys guide the content of NASA's science programs, they also help commit to the highest—help us commit to the highest priorities identified by the science community. The decadal surveys keep us honest and focused on top priorities when funding constraints or competing interests arise.

However, consistently following and implementing decadal priorities has not always been easy. The complexity involved in ambitious, large-scale missions has led, in some cases, to significant cost and schedule growth, so we must be vigilant in ensuring that NASA is as innovative in program and cost management as it is in advancing scientific discovery. How can NASA and the community both encourage ambitious breakthrough science while minimizing unanticipated costs and delays that may come with pushing the edges of innovation? And must pushing the edges of innovation and discovery always be equated to large and expensive missions? Or can the use of small satellites and CubeSats and hosted payloads, where appropriate, also help us acquire scientific observations and measurements at a lower cost?

It is clear we have a lot to discuss, and I look forward to our witnesses' testimony and perspectives on these critical issues.

[The prepared statement of Chairwoman Horn follows:]

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It is clear we have a lot to discuss, and I look forward to our witnesses' testimony and perspectives on these critical issues.

Chairwoman HORN. The Chair now recognizes Ranking Member Babin for an opening statement.

Mr. BABIN. Thank you, Madam Chair. I appreciate it and appreciate all of you expert witnesses for your testimony.

Year after year, NASA amazes the world with new wonders to behold, and the Science Mission Directorate at NASA makes that happen. The Hubble Space Telescope has informed our understanding of the age of the universe, its rate of expansion, and provided a breathtaking perspective of our place in the cosmos with its Deep Field Image.

Other observatories like the Compton Gamma Ray Observatory, and the Chandra X-Ray Observatory, and the Spitzer Space Telescope returned stunning images of our universe's astronomical phenomena like supernova and neutron stars. The Curiosity Rover observed whirlwinds called "dust devils" on Mars and continues to search for the building blocks of life on the red planet. We've sent probes to every planet in our solar system, traveled through the rings of Saturn and landed on its surface with the Cassini-Huygens mission, explored Jupiter and its fascinating moons with the Galileo and Juno missions, and most recently visited Pluto with the New Horizons probe and revealed its heart-shaped icy surface.

We've located, tracked, characterized, and visited asteroids and comets with missions like Stardust, Deep Impact, WISE (Wide-field Infrared Survey Explorer), and Dawn. NASA missions like Kepler and the TESS (Transiting Exoplanet Survey Satellite) discovered thousands of planets around other stars, some of which may be habitable zones that could harbor life. We've sent spacecraft like the Parker Solar Probe to interrogate the sun and beyond the solar system into interstellar space with the Voyager spacecraft.

NASA developed the next generation of weather satellites for NOAA that decreases the warning time for severe weather events like hurricanes and tornadoes and provides reliable forecasts for farmers and fishermen, pilots, and every American. These are stunning achievements.

However, NASA has more to offer. NASA continues to develop the James Webb Space Telescope (JWST), the flagship follow-on to the Hubble Space Telescope that stands to fundamentally rewrite the textbooks. The Europa Clipper mission will explore Jupiter's icy ocean world that has intrigued scientists because of its potential to harbor life. Lucy and Psyche will explore unique asteroids, and OSIRIS-REx will even return a sample to Earth. The Mars 2020 rover will also prepare and store samples for a future sample return mission. We live in a very exciting time.

As NASA continues to awe us with scientific discoveries, we should be ever mindful that the Science Mission Directorate is also responsible for critical national missions that go beyond science. Congress charged NASA to find 90 percent of 140-meter asteroids that could harm the Earth by 2020. NASA carries out this vital task through SMD's Planetary Defense Coordination Office. NASA also operates a fleet of heliophysics spacecraft that informs our understanding of space weather that impacts everything from the electrical grid to communications and GPS signals. Similarly, NASA's Joint Agency Satellite Division manages the development of our Nation's critical weather satellites that serve as the very backbone of weather forecasting.

The Administration's budget request for science is very strong. And while it is a reduction from the Fiscal Year 2019 appropriation, it represents the highest budget request in history. The request was developed before the final appropriation for FY 2019 was even determined. If you compare this request to the final budget request of the Obama Administration, which many on this Committee supported, this request is much stronger. This request represents an increase of $1.1 billion, or 21 percent, over President Obama's last budget request for discretionary spending in FY 2017. That same FY 2017 budget request from the previous Administration projected a notional FY 2020 request of $5.627 billion.

President Trump's proposed science budget is $6.39 billion. That is $767 million, or 13.6 percent, more than President Obama planned for FY 2020. This is a solid request for science at NASA, but that doesn't mean that we should let our guard down.

Cost overruns like those experienced by JWST, the Mars 2020 rover, and ICESat–2 (Ice, Cloud and land Elevation Satellite) come at the expense of other missions like WFIRST (Wide Field Infrared Survey Telescope) and PACE (Plankton, Aerosol, Cloud, ocean Ecosystem) and threaten the health of not just the Science Mission Directorate, but also the entire agency. And that's why strong leadership is required to instill discipline in program management early and often. Tough choices have to be made to ensure that overruns do not threaten the existing and future missions. The Nation's space science enterprise cannot afford to have another JWST or ICESat–2.

And I yield back.

[The prepared statement of Mr. Babin follows:]

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Chairwoman HORN. Thank you, Mr. Babin.

The Chair now recognizes the Chairwoman of the Full Committee, Ms. Johnson, for an opening statement.

Chairwoman JOHNSON. Thank you very much, and good morning, Madam Chair, for holding this hearing on "Discovery on the Frontiers of Space: Exploring NASA's Science Mission."

Scientific research has been part of NASA's mission since the agency's founding. The *National Aeronautics and Space Act of 1958*—the expansion of human knowledge, a phenomena in the atmosphere and space and one of the eight objectives of the Nation's aeronautical and space activities.

Since the 1958 Act, NASA and the Nation have invested in the systematic scientific exploration of our planet, bodies in the solar system, the Sun, and the universe that have answered many questions, and generated many more. That scientific exploration has come with surprises. For example, who would have imagined that Pluto may be—may have active volcanoes spewing ice or that there is a mysterious force causing our universe to expand at an accelerating rate?

NASA has been at the forefront of discoveries such as these in space and Earth science since its inception with a cadence of small, medium, and large missions and supporting research and technology that keep the public engaged, inspired, and learning.

That's why it perplexes me as to why the Administration would even consider raiding Science to pay for a Moon program. Yet that may be where NASA is headed, despite the Administration—Administrator's assurances to the contrary. The 1-year budget amendment that came over in May would give the Administrator carte blanche authority to move funds among NASA's accounts from this year forward if he determines that the transfers are necessary in support of establishment of a U.S. strategic presence on the Moon. Why? Because the Administration, it seems, may not request in the coming years what NASA actually needs for its crash program to get astronauts to the Moon by 2024.

According to media articles, NASA officials are stating that hard choices lie ahead and that NASA find money for the Moon program from within the agency's other programs. This isn't a new tactic. The George W. Bush Administration, which initiated the last Moon program, tried the same approach. According to a 2006 National Academies report, the Bush Administration indicated its intention to cut significantly from Science to pay for its Moon program. The scars from those cuts are still felt today, especially in the life and physical sciences research program, which experienced reductions that decimated the pipeline of microgravity research and drove scientists to other fields.

The talented women and men at NASA and its partner institutions deserve better. Those who have become acquainted with the NASA workforce know that they will work tirelessly in an effort to meet a goal. Passion can take us so far, but it alone can't build the rockets and the landers, the spacesuits and the habitats, and all of the other elements needed for a safe and sustainable Moon-Mars program. NASA needs a solid plan, sufficient resources, people, and infrastructure over multiple years to enable deep space human exploration. Starving science to fund human exploration is not the answer.

I know our witnesses will have much to say about the opportunities and challenges facing NASA's space and Earth sciences, and I look forward to your testimony. I thank you and yield back.

[The prepared statement of Chairwoman Johnson follows:]

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NASA needs a solid plan, sufficient resources, people, and infrastructure over multiple years to enable deep space human exploration. Starving Science to fund human exploration is not the answer. I know our witnesses will have much to say about the opportunities and challenges facing NASA's space and Earth sciences. I look forward to their testimony.

Thank you and I yield back.

Chairwoman HORN. Thank you, Madam Chairwoman.

If there are any other Members who wish to submit additional opening statements, your statements will be added to the record at this point.

At this time, I would like to introduce our witnesses today. Our first witness is Dr. Thomas Zurbuchen. Since October, Dr. Zurbuchen has served as the Associate Administrator for NASA's Science Mission Directorate. Previously, Dr. Zurbuchen was a Professor of Space and Aerospace Engineering at the University of Michigan in Ann Arbor. He was also the university's founding Director of the Center for Entrepreneurship in the College of Engineering.

Dr. Zurbuchen's experience includes research in solar and heliospheric physics—that's a mouthful—experimental space research, space systems, and innovation and entrepreneurship.

During his career, Dr. Zurbuchen has been involved with several NASA science missions: Ulysses, the MESSENGER spacecraft to Mercury, and the Advanced Composition Explorer. He has also been part of two National Academies' standing committees, as well as various science and technology definition teams for new NASA missions.

Dr. Zurbuchen earned his master of science and Ph.D. in physics from the University of Bern in Switzerland.

Our next witness is Dr. Chelle Gentemann. Dr. Gentemann is a Senior Scientist at Earth and Space Research, a nonprofit research institute in Seattle, Washington, and an affiliate of the University of Washington.

Previously, Dr. Gentemann served as a visiting scholar to the NASA Jet Propulsion Laboratory and Senior Principal Scientist at Remote Sensing Systems. Dr. Gentemann is currently the Co-Chair of the standing committee on Earth Science and Applications from Space and is on the Academies' Intelligence, Science, and Technology Experts Group. Her most recent research focuses on using cloud computing, open-source software development, machine learning, and algorithm development using remote sensing data, air-sea interactions, and upper ocean physical processes.

Dr. Gentemann received her bachelor's degree in science from the Massachusetts Institute of Technology, a master of science in physical oceanography from the Scripps Institution of Oceanography, and a doctorate in meteorology and physical oceanography from the University of Miami. Welcome.

Our third witness is Dr. David Spergel. Dr. Spergel is the Charles Young Professor of Astronomy at Princeton University. He is the founding Director of the Center for Computational Astrophysics at the Flatiron Institute. Dr. Spergel is the former Chair of the Space Studies Board and is currently the Co-Chair of the Wide Field Infrared Survey Telescope, WFIRST, science team. Dr. Spergel's work is focused on using laboratory experiments and astronomical observations to probe the nature of dark matter and look for new physics.

Dr. Spergel earned his bachelor's degree from Princeton University and his doctorate in astronomy from Harvard University.

Our fourth and final witness is Dr. Mark Sykes. Dr. Sykes is the Chief Executive Officer and Director of Planetary—of the Planetary Science Institute. He has served as the Chair of the Division for Planetary Sciences of the American Astronomical Society. He is also Co-Investigator on the NASA Dawn mission project to the asteroid Vesta and the dwarf planet Ceres.

He received his bachelor's in physics from the University of Oregon where he studied the first known black hole system, Cygnus X-1. He received a master of electronic science from Oregon Graduate Center and a Ph.D. in planetary sciences from the University of Arizona.

Welcome to all of you. As our witnesses, you should know that you will each have 5 minutes for your spoken testimony, and your full written testimony will be included in the record for the hearing. When you have completed your spoken testimony, we will begin with questions from each Member, and each Member will have 5 minutes on—to question the panel.

We will start today with Dr. Zurbuchen. Dr. Zurbuchen.

TESTIMONY OF DR. THOMAS H. ZURBUCHEN, ASSOCIATE ADMINISTRATOR, SCIENCE MISSION DIRECTORATE, NASA

Dr. ZURBUCHEN. Thanks so much. Chair Horn, Ranking Member Babin, and Members of the Subcommittee, I'm pleased to testify today. I want to thank you for your commitment to NASA and to NASA science.

We'll discuss how this FY 2020 budget request enables us to succeed in three strategic focus areas: Advancing national exploration goals, maintaining a balanced science program, and delivering true impact through our investments. Regarding advancing national exploration goals, Artemis is NASA's lunar exploration program that will send humans to the Moon by 2024, develop a sustainable human presence there in 2028, and set the stage for human exploration of Mars, the ultimate goal of NASA's human exploration program.

Robotic missions delivered by commercial landers will be the first Artemis elements to land on the Moon. Through NASA Science's CLPS (Commercial Lunar Payload Services) initiative, we are incentivizing speed and drawing on our commercial and international partners to enable science investigations and technology demonstrations on the Moon ahead of human return.

We recently selected three commercial Moon landing service providers for the earliest missions in 2020-2021. These missions will acquire new science measurements and enable important technology demonstrations to provide data that will inform future exploration systems needed for astronauts. The amended budget request also includes $90 million for the purchase of a commercial service—commercial services to deliver a rover to the Moon.

SMD is committed to executing a balanced and integrated science program that is informed by the decadal surveys of the National Academies. In planetary science, NASA's robust Mars program is providing groundbreaking science and exploration information. This request supports continued progress of the Mars 2020 rover, which will search for the evidence of life on the red planet and collect a cache of samples. With this request, NASA will start development of a Mars sample return mission, completing the first round-trip to another planet.

In parallel, the cutting-edge Europa Clipper, a strategic mission to fly to Jupiter's moon, will be our first step in exploring ocean worlds and their potential habitability for extraterrestrial life. Competitively selected missions like OSIRIS-REx and the Mars lander InSight are critical ingredients to our program, as are the Psyche and Lucy missions to explore distant asteroids.

In astrophysics, the budget supports the revised launch date of James Webb, the largest and most powerful space telescope to date. Webb will examine the first galaxies that formed in the atmospheres of nearby planets outside our solar system. After the successful planet-counting mission Kepler, we are now focused on TESS which will provide a rich catalog of worlds around nearby stars including valuable targets for Webb to explore in the future.

In August 2018, our heliophysics program launched Parker Solar Probe. Parker has already completed two of its 24 near-solar passes flying to within 15 million miles of our star, the sun. We recently selected the IMAP (Interstellar Mapping and Acceleration Probe) mission that will image the outer boundary of the sphere of influence of our sun.

In 2018, NASA launched two strategic missions recommended by the Earth-science decadal. GRACE Follow-On is measuring the mass of ice sheets and glaciers and tracking Earth's water movements across the planet, while ICESat–2 is providing unprecedented data on the typogography of ice—topology, of course, interesting word—of ice, forests, and oceans. ECOSTRESS (ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station) and GEDI (Global Ecosystem Dynamics Investigation) are now on the ISS (International Space Station) measuring agricultural water use and drought conditions, as well as creating 3-D maps of the world's forests. The request funds continue progress on Landsat 9 for a launch in '21 together with our U.S. Geological Survey (USGS) partners.

NASA's Earth science continues using innovative partnerships and new approaches, including the acquisition of commercial data products from small satellite constellations. Our work has societal value to the U.S. and beyond. Our Earth science program teams with partners to develop and demonstrate applications in areas like disaster management, public health and resource management to provide direct benefit to our Nation. Heliophysics-funded research enables the predictions necessary to safeguard life and society on Earth and the outward journey of humans and robotic explorers.

And in addition, NASA looks for near-Earth objects (NEOs) to assess if they pose any threat to us. We found 96 percent of the potentially hazardous NEOs that are over 1 kilometer in diameter, and one-third of those at 140 or more. The request funds the technology to deflect such bodies using the DART (Demonstration for Autonomous Rendezvous Technology) mission.

With this request, SMD will help pave the way for the success of Artemis program, initiate the first round-trip mission to the red planet with a Mars sample return mission, and continue investing in the groundbreaking work of our scientists, engineers, and technologists to—every day to answer humanity's most fundamental questions and to inspire learners of all ages.

Thank you for the opportunity to testify here today.

[The prepared statement of Dr. Zurbuchen follows:]

HOLD FOR RELEASE UNTIL PRESENTED
BY WITNESS
June 11, 2019

Statement of

Thomas Zurbuchen, Ph.D.
Associate Administrator for Science Mission Directorate
National Aeronautics and Space Administration

before the

Subcommittee on Space and Aeronautics
Committee on Science, Space, and Technology
U.S. House of Representatives

Overview

Chair Horn, Ranking Member Babin, and Members of the subcommittee, I am pleased to have this opportunity to discuss the amended FY 2020 budget request for NASA's Science Mission Directorate (SMD). Before I go further, I want to thank you for your commitment to NASA and to SMD; our directorate is in a strong position thanks to your leadership and bipartisan support.

SMD leverages space-, air-, and ground-based assets to answer fundamental questions about Earth, the solar system and the universe, and our place in the cosmos. Our scientists, engineers, and technologists work with a global community of researchers to provide the scientific discoveries that advance critical understanding and inform decision-making. Whether through disaster response, natural resource management, planetary defense, or space weather monitoring, NASA provides tangible benefits that help protect and improve life on Earth. At the same time, NASA is leading the quest to answer some of the most pressing human questions, among them how Earth and the universe evolved, how life emerged, and whether we are alone in the universe.

The amended FY 2020 budget requests $6,393.7 million for NASA Science, including $2,712.1 million for Planetary Science, $844.8 million for Astrophysics, $352.5 million for the James Webb Space Telescope (JWST), $704.5 million for Heliophysics and $1,779.8 million for Earth Science. Today I would like to talk through how this request enables us to achieve success in three strategic focus areas: advancing national exploration goals, maintaining a balanced and integrated science program, and delivering true impact through our investments. Integrated throughout is our concerted effort to seek and execute new partnerships that will allow us to leverage the innovation, resources, and expertise of the full breadth of the global science enterprise, including other U.S. and foreign government agencies, as well as commercial, academic, and other non-governmental partners.

Advancing National Exploration Goals

Artemis is the name of NASA's lunar exploration program that will send the first woman and the next man to the South Pole of the Moon by 2024 and develop a sustainable human presence on the Moon by 2028. Artemis takes its name from the twin sister of Apollo and goddess of the Moon in Greek mythology.

NASA is working to build a sustainable, open architecture that returns humanity to our nearest neighbor. We are building for the long term, and this time are going to the Moon to stay. We are intending to design an open, durable, reusable architecture that will support exploration for decades to come. Sustainability requires reusable systems and partnerships from across the commercial sector and around the world. Robotic scientific missions delivered by commercial landers will be the first Artemis elements to land on the Moon.

The agency is incentivizing speed and drawing on commercial and international partners as it looks to land humans on the Moon within five years. NASA is completing development of both the Orion spacecraft that will carry humans to lunar orbit, and the Space Launch System (SLS) rocket that will launch Orion. NASA is pressing forward toward the Artemis 1 mission, an uncrewed test flight of Orion and SLS as an integrated system around the Moon. This will be followed by the Artemis 2 mission that will be the first test flight with human crew to the lunar vicinity aboard SLS and Orion. Then, the Artemis 3 mission will send the first crew to the lunar surface using commercial human landing services that depart from the Gateway outpost orbiting the Moon. With the rapid development of the commercial landing services and the Gateway, we will have access to more of the Moon than ever before. On May 23, 2019, NASA announced that Maxar Technologies would develop and demonstrate capabilities for the Gateway through a component called the power and propulsion element (PPE). The PPE, the first element of the Gateway, will launch to lunar orbit and fly by means of a technology called solar electric propulsion, but with three times more powerful than what has flown so far. This PPE will provide communications for human and robotic landers as well as visiting vehicles.

There is intense interest in what we can discover at the Moon. The lunar samples returned during the Apollo Program dramatically changed our view of the solar system, and scientists continue to unlock new secrets from the samples. Yet, we are just scratching the surface of knowledge about the Moon. By studying the geology of the Earth, the Moon, and Mars – the three planetary bodies we know the most about - and the ways in which they are similar and different from each other, we can learn fundamental aspects about how planets and planetary systems form. We know the Moon can tell us more about our own planet, and even our own Sun. There is so much more to learn – knowledge we can acquire with a sustained human and robotic presence on the Moon. NASA will conduct many more science investigations and technology demonstrations on the Moon ahead of a human return through its Commercial Lunar Payload Services (CLPS) initiative.

The Lunar Discovery and Exploration Program (LDEP), established within SMD, advances an integrated, innovative and sustainable strategy for exploration. LDEP is rooted not only in fostering improved collaboration across the Agency, but on truly leveraging interagency, international, and commercial partnerships to enable the payloads and services that will address the Nation's lunar exploration, science and technology demonstration goals. The synergy between robotic and human exploration assets enables valuable opportunities for science that cut across our science disciplines, allowing us to take advantage of the Moon both as a destination and as a unique vantage point to discover the secrets of the universe, and through it protect and improve life on Earth.

Our two-phased effort to implementing the exploration science goals, demarcated by the first human return mission to the lunar surface in 2024, has already begun. In November 2018, NASA selected nine U.S. companies to bid on delivery services to the lunar surface through CLPS contracts. Lunar payloads from a variety of customers, including NASA, will fly on contracted missions starting in 2020, enabling critical technology demonstrations and scientific observations. In February 2019, NASA also selected 10 proposals for the Development and Advancement of Lunar Instrumentation (DALI) program, which will support instruments that will fly on future lunar missions. Building on these efforts, the amended budget request includes $90 million for the purchase of commercial services to deliver a rover to the Moon. These additional funds will allow SMD, through our commercial partners, to send a robotic mission to explore the Moon's polar regions in advance of the Artemis program's first human landing. Interfaces like these enable us to increase our understanding of the lunar surface while advancing the interests of both science and human exploration, setting us up for success for the 2024 human landing and our sustained presence on the Moon. Most recently, on May 31, we announced the selection of the first commercial Moon landing service providers that will deliver science and technology payloads as part of CLPS. These missions will acquire new science measurements and enable important technology demonstrations, whose data will inform the development of future landers and other exploration systems needed for astronauts to return to the Moon by 2024.

LDEP also enables continued operations of NASA's Lunar Reconnaissance Orbiter (LRO), which marks its tenth anniversary this month. LRO continues to help scientists characterize the lunar surface, providing insights into lunar resource analysis that could support future human exploration.

Maintaining a Balanced Science Program

NASA remains focused on exploring even those worlds that humans may never visit, building missions that are changing not only what we know, but also how we think. NASA robotic missions have visited all the planets of the solar system, and the Parker Solar Probe has broken the record as the closest spacecraft ever to the Sun. While the long-lived Opportunity Rover has finally ceased functioning, the even longer-lived Voyager spacecraft have left the solar system. The search for life beyond Earth takes its next step with our planned mission to Europa. The unparalleled James Webb Space Telescope (Webb) will open a new chapter in humanity's ongoing quest to explore and understand our universe.

To ensure not only leadership today, but also tomorrow, SMD is committed to executing a balanced and integrated science program that is informed by the decadal surveys of the National Academies of Science, Engineering and Medicine. We strike this balance by delivering success in strategic flagship missions as well as achieving the right cadence of competed opportunities led by principal investigators (PIs) to empower the best and brightest in the science community.

In Planetary Science, NASA's robust Mars Exploration Program is providing both ground-breaking science and the critical precursor data and information we need to support future human missions to the Red Planet. Mars remains the Agency's horizon goal for human space exploration. A vigorous Mars Exploration program is essential to our pursuit of this goal. The budget request supports continued progress of the Mars 2020 rover, which – after an intensive effort to identify the most promising landing site – will head to the Jezero Crater following a July 2020 launch. A precursor to human missions to Mars, Mars 2020 will continue to search for evidence of life on the Red Planet and collect a cache of core samples. In 2020, NASA will commence studies and development of a Mars Sample Return mission – the highest-priority strategic mission identified by the scientific community in the most recent planetary science decadal survey and endorsed in the 2018 midterm assessment – that would allow for the return of the Mars 2020 rover samples. Leveraging commercial and international partnerships, such as with the European Space Agency, this mission may launch as early as 2026.

In parallel, the cutting-edge Europa Clipper, a strategic mission to fly by Jupiter's moon, will be our first step in exploring ocean worlds and their potential habitability for extraterrestrial life.

Earlier this year, on New Year's Day, NASA celebrated the first flyby of the Kuiper Belt object called MU69/Ultima Thule with our New Horizons mission. The data collected from over four billion miles away from Earth will help answer basic questions about the surface properties, geology, and atmospheres of these primitive bodies.

In December 2018, NASA's first asteroid sampling mission, the Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx), entered orbit around Bennu, the smallest object a spacecraft has ever orbited. In 2020, OSIRIS-REx will have completed its mapping of Bennu, informing selection of the most promising sample collection site. Its measurements of this potentially hazardous object (Bennu's orbit could bring it relatively close to Earth at the end of the next century), will not only shed light on the early history of our Solar System, but will also inform the design of future missions to mitigate possible asteroid impacts on Earth.

In November 2018, the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) lander (selected through the competitive Discovery program) reached the Martian surface, marking the Agency's eighth successful soft landing on the Red Planet. A robot geologist, InSight will yield new discoveries about the Martian interior, providing an unprecedented look at its core structure and heat flow. Cruising behind InSight were two experimental, briefcase-sized spacecraft named Mars Cube One (MarCO) – the first ever planetary CubeSats – which successfully relayed data back to Earth from the InSight lander during its descent to the Martian surface.

The budget request supports continued development of the next Discovery missions, Lucy and Psyche, which have the potential to open new windows on one of the earliest periods in the history of our solar system.

Built as a cohesive program for Near-Earth Object (NEO) detection and mitigation technology development, NASA's Planetary Defense Program will continue to fund the NEO Observations project and development of a space-based infrared instrument for detecting NEOs with this year's budget request. Meanwhile, the Double Asteroid Redirection Test (DART) to demonstrate the kinetic impact technique for asteroid deflection will continue to make progress towards its planned 2021 launch.

Turning to our investments in Astrophysics, the 2020 budget request accommodates the funds needed to support the revised March 2021 launch date of the James Webb Space Telescope, the largest and most powerful space telescope to be developed to date. Webb will join NASA's family of observatories to examine the first stars and galaxies that formed, viewing the atmospheres of nearby planets outside our solar system and informing our understanding of the evolution of our own solar system. In order to maintain a balanced science program that optimizes overall scientific return, the FY 2020 budget request again proposes termination of the Wide Field Infrared Survey Telescope (WFIRST), given its significant cost and higher priorities within NASA.

The budget request also supports operations for the airborne Stratospheric Observatory for Infrared Astronomy (SOFIA), a partnership with the German Aerospace Center that allows astronomers to study the solar system and beyond in ways that are not possible with ground-based telescopes.

In 2018, after nine years of searching for planets outside our Solar System, NASA bid farewell to the Kepler mission. Kepler discovered almost 2,700 new exoplanets, bringing the total from all sources to over 3,900 known exoplanets. Kepler's legacy serves as the foundation for NASA's next planet-hunting mission, the Transiting Exoplanet Survey Satellite (TESS), launched in April 2018. Just 10 months into science operations, TESS had confirmed 15 new exoplanets, 5 new multi-planet systems, and 639 exoplanet candidates. During its two-year primary mission, TESS will observe nearly the whole sky, providing a rich catalog of worlds around nearby stars, including valuable targets for Webb to explore.

The Heliophysics Division adopts a holistic approach to the study of the Sun and its connection to Earth and other planets – venturing to the very edge of the Sun's influence and beyond. In December 2018, Voyager 2 exited the heliosphere, the protective bubble of particles and magnetic fields created by the Sun, a milestone only achieved once before – by Voyager 1 in 2012. In over 40 years in space, Voyager 2 has traveled a staggering 18.5 billion miles and is NASA's longest-running mission.

In 2018, several successful launches expanded the Heliophysics System Observatory, including the August 2018 launch of the Parker Solar Probe. Having completed its first of 24 planned orbits around the Sun in January 2019, Parker Solar Probe has already made two passes within 15 million miles of our star.

In July 2018, NASA selected the Interstellar Mapping and Acceleration Probe (IMAP), a strategic mission identified as a priority in the most recent solar and space physics decadal survey, to launch in 2024 to study the boundary of the outer solar system where the solar wind ends. Further expanding our understanding of the heliosphere, in 2020, NASA will launch Solar Orbiter, a joint collaboration led by the European Space Agency, into orbit around the Sun.

Launching in 2019, the Ionospheric Connection Explorer (ICON) instrument will help provide the most comprehensive observations of the ionosphere – a region of charged particles in Earth's upper atmosphere. ICON will join the Global-scale Observations of the Limb and Disk (GOLD) instrument, which has been studying the dynamics of the ionosphere since its launch in 2018 as the first NASA science mission to fly as a commercially hosted payload.

NASA continues to work with its agency partners to reduce gaps between space weather research and operations. The budget supports the Heliophysics Space Weather Science and Applications project to further strengthen the feedback between fundamental research and operational forecasting needs by improving the transition of science results into operational products. The budget also provides for a potential new Small Explorer-class space weather mission. This will lay the groundwork for a future Space Weather Mission line to focus on resolving fundamental science problems required to improve space weather prediction, and serve as a pathfinder for observation technology for the National Oceanic and Atmospheric Administration's operational space weather missions.

In 2018, NASA launched two strategic missions recommended by the 2007 Earth Science decadal survey Gravity Recovery and Climate Experiment Follow-On (GRACE-FO); and Ice, Cloud and land Elevation Satellite-2 (ICESat-2). The twin satellites of GRACE-FO are continuing the original GRACE mission's 15-year legacy (2002-2017) of measuring the changing mass of ice sheets and glaciers and tracking Earth's water movement across the planet. ICESat-2, the follow-on to NASA's ICESat mission (2003-2009), is providing unprecedented data on the topography of ice, forests, and oceans. In November 2018, the Operation IceBridge 2018 Antarctic Field Campaign concluded successfully after flying under ICESat-2 orbits to validate and verify the new satellite's measurements.

In addition, NASA Earth Science is collaborating with the Human Exploration and Operations Mission Directorate to utilize the International Space Station (ISS) for Earth observations. NASA Earth Science launched two low-cost, competitively selected missions to the ISS in 2018. The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) instrument is measuring agricultural water use, vegetation stress, and drought warning conditions. In December 2018, the similarly low-cost, competitively selected Global Ecosystem Dynamics Investigation (GEDI) vegetation canopy lidar instrument was launched to the ISS and is now embarked on its science mission to make 3D maps of the world's forests.

The FY 2020 budget request also funds continued progress of Landsat 9 for a launch as early as FY 2021. As part of the Sustained Land Imaging program architecture, Landsat 9 will enable continuity of the critical, long-term land imaging data record begun in 1972 with NASA's joint agency partner, the U.S. Geological Survey. Consistent with the FY 2019 budget request, the FY 2020 request proposes termination of the Plankton Aerosol Cloud ocean Ecosystem (PACE), and Climate Absolute Radiance and Refractivity Observatory Pathfinder (CLARREO-PF) missions.

NASA Earth Science continues to explore innovative partnerships and new approaches, including the acquisition of commercial data products from small satellite constellations. In September 2018, the Earth Science Division awarded contracts to three commercial data products providers. Through this pilot program, NASA-funded researchers will examine the scientific value of the data to help determine the utility of the private sector's constellation-based products for advancing NASA's science and applications development goals. The 2020 budget request continues support for the integration of NASA Earth Science efforts with non-governmental partners through these and other activities, such as commercial hosting and new partnerships (such as the NASA-Conservation International collaboration announced in February 2018).

Finally, upcoming selections and opportunities will demonstrate NASA's continued commitment to PI-led, competed opportunities, a priority highlighted in the most recent decadal surveys of the scientific communities we support. By the end of FY 2019, NASA plans to select the next New Frontiers mission for Planetary Science, the next Heliophysics Explorer missions, and the Earth Venture Instruments-5 (EVI-5) instrument. We also plan to release Announcements of Opportunity for the next Discovery mission, and the next Astrophysics Small Explorer and Mission of Opportunity missions. Our 2020 budget request puts us in an even stronger footing to achieve the right mix of large strategic missions and competed small and medium-class opportunities. For example, it enables us to fully support competed Astrophysics missions at the decadal survey-recommended cadence, fully fund Earth Science's planned future solicitations in all three competed strands, and implement the Heliophysics' DRIVE (Diversify, Realize, Integrate, Venture, Educate) initiative, increasing the competed research program to about 15 percent of the budget request.

Delivering Impact

I have talked about many NASA programs, but I would like to leave you with an important message -- that NASA science directly supports decision-making, helping improve our society and quality of life. Our Earth Science program teams with government and commercial partners in the U.S. and internationally to use the measurements and understanding to develop and demonstrate applications that provide direct benefit to our Nation, and indeed all of humanity.

NASA also accumulates, archives, and distributes data collected by the Heliophysics System Observatory, a fleet of operating spacecraft. Combining the measurements from all of these observing platforms enables interdisciplinary, connected systems science across the vast spatial scales of our solar system. This collective asset enables the data, expertise, and research results to contribute directly to fundamental research on solar and space plasma physics and to the national goal of real-time space weather prediction. NASA teams support day-to-day mission operations for NASA spacecraft and data analysis to advance the state of space science and space weather modeling. NASA conducts science community-based projects to evaluate research models containing space weather information that is of value to industry and government agencies. Heliophysics data centers archive and distribute the science data from operating missions in the Living With a Star (LWS), Solar Terrestrial Probes (STP), Research, and Explorer programs. The science of heliophysics, including space weather, enables the predictions necessary to safeguard life and society on Earth and the outward journeys of human and robotic explorers. For example, the Global-scale Observations of the Limb and Disk (GOLD) mission was the first NASA science instrument launched aboard a commercial spacecraft. From its location parked over the western hemisphere in geostationary orbit, the mission enables scientific understanding and situational awareness of ionospheric phenomena that can cause dramatic impacts on communications and other space weather effects.

In addition, NASA's Near Earth Objects Observation (NEOO) project, using ground and space-based assets, looks for Near-Earth Objects (NEOs) that have any potential to collide with Earth and characterizes them to assess if any could do significant damage to the planet. NEOs range in size from a few meters to approximately 34 kilometers, with smaller objects being two orders of magnitude more numerous than larger objects. The NEOO project supports a network of search and characterization observatories and the data processing and analysis required to understand the near-Earth population of small bodies. Since NASA's search started in 1998, the project has found over 96 percent of these objects that are 1 kilometer and larger, and about 34 percent of all those larger than 140 meters in size. NEOs discovered and characterized by the project may also be viable targets for future robotic and crewed exploration, and possible eventual candidates for asteroid mining operations.

As we begin the summer season, we are reminded that heat waves are one of the leading causes of weather-related deaths in the United States. NASA satellite data are being used, not only to track these extreme temperatures, but also to measure the height of trees, data that helps city managers determine the best places to plant more sources of crucial shade. Other satellite data are used to identify who is most at-risk when the temperatures rise, and, when combined with air quality measurements, identify when to issue heat-related advisories. Heat also brings other health-related risks, and NASA is also helping track mosquitoes. These tiny, disease-carrying, cold-blooded creatures love hot, wet weather. Public health departments from California to Maryland are taking NASA data on soil moisture, plant coverage, and land temperature to create maps that combine this information with, for example, reported outbreaks of West Nile Virus. They're using these maps to inform warnings, to define strategies for spraying, and develop more efficient and effective ways to keep Americans safe.

Conclusion

With Webb poised to look out into the cosmos and back to the time when the first stars were forming, humans landing on the Moon, and constellations of spacecraft exploring the solar system and our home planet, NASA's amended FY 2020 request supports what is truly a golden age of exploration.

With the amended FY 2020 request, SMD will help pave the way for the success of the Artemis program, initiate the first round-trip mission to the Red Planet with a Mars sample return mission, and continue investing in the groundbreaking work our scientists, engineers, and technologists do every day to answer humanity's most fundamental questions. With this investment, we will provide critical data and capabilities for future robotic and crewed missions, increase our understanding of our home planet, and move out on ambitious programs to study the far reaches of our solar system, and beyond.

Thank you for the opportunity to testify before you today. I would be pleased to respond to your questions.

Dr. Thomas Zurbuchen is the Associate Administrator for the Science Mission Directorate at the Agency's Headquarters in Washington, D.C.

Previously, Zurbuchen was a professor of space science and aerospace engineering at the University of Michigan in Ann Arbor. He was also the university's founding director of the Center for Entrepreneurship in the College of Engineering. Zurbuchen's experience includes research in solar and heliospheric physics, experimental space research, space systems, and innovation and entrepreneurship.

During his career, Zurbuchen has authored or coauthored more than 200 articles in refereed journals on solar and heliospheric phenomena. He has been involved with several NASA science missions -- Ulysses, the MESSENGER spacecraft to Mercury, and the Advanced Composition Explorer (ACE). He also has been part of two National Academy standing committees, as well as various science and technology definition teams for new NASA missions.

Zurbuchen earned his Ph.D. in physics and master of science degree in physics from the University of Bern in Switzerland.

His honors include receiving the National Science and Technology Council Presidential Early Career for Scientists and Engineers (PECASE) Award in 2004, a NASA Group Achievement Award for the agency's Ulysses mission in 2006, and the Swiss National Science Foundation's Young Researcher Award in 1996-1997.

Chairwoman HORN. Thank you, Dr. Zurbuchen. Dr. Gentemann.

TESTIMONY OF DR. CHELLE L. GENTEMANN, SENIOR SCIENTIST, EARTH AND SPACE RESEARCH, AND CO-CHAIR, COMMITTEE ON EARTH SCIENCE AND APPLICATIONS FROM SPACE, SPACE STUDIES BOARD, NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE

Dr. GENTEMANN. Thank you. Chairwoman Horn, Ranking Minority Member, and Members of the Committee, I want to thank you for the opportunity to testify today.

As Chairwoman Horn said, I am Co-Chair of the National Academies' standing Committee on Earth Science and Applications from Space, CESAS. However, the opinions that I express today should be attributed to me unless stated otherwise.

CESAS produced the most recent 10-year roadmap or decadal survey to guide U.S. investments in Earth systems science for societal benefit. It's charged with monitoring the progress in the implementation of the decadal survey's recommendations. The decadal survey discusses in detail the benefits to the Nation from a robust Earth science program at NASA, NOAA (National Oceanic and Atmospheric Administration), and USGS. Drawing on their own expertise and hundreds of solicited concept proposals and white papers from the community, about 100 of the Nation's leading Earth scientists, space system engineers, and policy experts worked for almost 2 years to develop a consensus on Earth-science priorities.

The survey made recommendations for the programs of all of its sponsors, but I will focus on those directed at NASA today. Most importantly, these are to complete the series of existing or previously planned observations from the 2007 survey called the Program of Record. To implement the designated essential observations, which are cost-capped medium- and large-size observing systems, to implement Earth System Explorer high-priority observations, which are cost-capped medium-size observing systems, to create a new program element called Incubator to advanced future capabilities and to continue the cost-capped Earth Venture line from the 2007 decadal, along with the addition of a new element called Continuity designed to facilitate development of low-cost means to sustain critical observations. The survey report presents a plan for an integrated program.

Completing the Program of Record is important because the decadal survey recommendations assume and build on this baseline from the 2007 decadal survey. The Program of Record includes both PACE and CLARREO (Climate Absolute Radiance and Refractivity Observatory) Pathfinder. Elimination of these missions in the Program of Record undermines the entire decadal survey planning and prioritization process.

PACE supports multiple research thrusts and is a key element in the survey's planned constellation of satellites that will give scientists and policymakers a clearer understanding of how to use Earth systems science for societal benefit.

CLARREO Pathfinder will provide the ability to intercalibrate instruments in space at accuracies 5 to 10 times beyond current capabilities.

Implementation of the full recommended program will require appropriations beyond that assumed by the decadal survey committee. In particular, additional funds would be needed to complete the full suite of designated, essential, and Earth System Explorer high-priority observations, as planned. These are foundational observations selected to ensure that the survey's highest priority science and application questions can be effectively addressed.

Finally, I note that the decadal survey process began in 2015. Rapid advancements in using commercial cloud computing and open-source software for science have outpaced planned activities. The survey didn't plan for the additional resources needed for a wholesale move of NASA data assets onto the cloud, support for the open-source software libraries that underpin the rapid scientific advancements and possible applications, or how to enable interdisciplinary science and commercial applications that will likely subsequently flourish.

In my view, this is one example of where comparatively small new investments have the potential to deliver outsized benefits. NASA's vast data resources and robust research community make it well poised to be a global leader in this effort. Jumpstarting these activities in NASA could grow the public-private cloud partnership and energize the research community.

As you consider NASA's reauthorization, I hope that the Committee sees the value of the decadal survey process and provides the funding to implement the decadal survey, including the Program of Record and both designated and Earth Explorer observables, as recommended.

Thank you for your time.

[The prepared statement of Dr. Gentemann follows:]

Statement of Dr. Chelle L. Gentemann
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Co-Chair National Academies of Sciences, Engineering, and Medicine (NASEM)
Standing Committee on Earth Science and Applications from Space (CESAS)
Affiliate, University of Washington Applied Physics Laboratory

Before the Subcommittee on Space and Aeronautics
Committee on Science, Space, and Technology
U.S. House of Representatives
June 11, 2019

Chairwoman Horn, Ranking Minority member, and members of the Committee, I want to thank you for the opportunity to testify today at the hearing on "Discovery on the Frontiers of Space: Exploring NASA's Science Mission." My name is Chelle Gentemann and I am a Senior Scientist at Earth and Space Research, a nonprofit research institute located in Seattle, Washington, an Affiliate at the University of Washington Applied Physics Laboratory, Co-Chair of the National Academies of Sciences, Engineering, and Medicine (NASEM) Standing Committee on Earth Science and Applications from Space (CESAS), and acting Chair of NOAA's Science Advisory Board's Data Archive and Access Requirements Working Group. I live in Santa Rosa, California, which you may recall was devastated in 2017 by wildfires.

I am a remote sensing physical oceanographer specializing in measuring ocean temperature from space and using those observations to advance our understanding of the upper ocean and how ocean variability imprints onto atmospheric weather. I've led several large commercial, governmental, and academic scientific coalitions funded by the National Oceanographic Partnership Program, NASA, NOAA, and the Office for Naval Research. This includes leading U.S. participation in an international science team organized to advance utilization of satellite observations.

Although parts of my testimony follow the specific recommendations and supporting text in the 2017-2027 Decadal Survey for Earth Science and Applications from Space (ESAS; "Decadal Survey"), the opinions I express should be attributed to me unless stated otherwise. I will provide thoughts on the scientific aspects of the Science Mission Directorate (SMD) portfolio to the subcommittee below.

Earth science and derived Earth information have become an integral component of our daily lives, our business successes, and society's capacity to thrive. The Decadal Survey and the popular version of that report that we've provided at this hearing[1] enumerate, in much greater detail than I can provide here, the benefits to the nation from a robust earth science program at NASA, as well as the earth observation programs at NOAA and the US Geological Survey.

Some 100 of the nation's leading earth scientists, space system engineers, and policy experts worked over nearly two years in developing the community consensus on earth science priorities that informs the Decadal Survey's recommendations for U.S. investments in support of earth science from space. The Decadal Survey builds on, and has as its highest priority, the completion of the Program of Record (POR). The POR includes both PACE and CLARREO Pathfinder (see more details below). Elimination of these missions in the POR undermines the entire Decadal Survey planning and prioritization process. PACE in particular supports multiple research thrusts and is a key element in the survey's planned constellation of earth observation satellites that will give scientists and policymakers a clearer understanding that will help prioritize climate change mitigation options and strategies. CLARREO Pathfinder will provide the ability to inter-calibrate instruments in space at accuracies 5 to 10 times beyond current capabilities. As you consider NASA's reauthorization, I hope that the committee sees the value of the Decadal Survey process and enables NASA to continue its implementation for all our benefit.

Finally, I note that rapid advancements in using commercial cloud computing and open source software for science have outpaced planned activities. I believe there are public-private partnership opportunities in cloud computing and open source software that could lead to breakthrough science and new commercial applications.

What are some of the most compelling scientific questions and opportunities in earth science and applications today?

The most recent National Academies' "Decadal Survey" for Earth Science and Applications from Space (ESAS), produced the report, Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space. A summary of this community report is appended to my testimony. The report begins by noting that understanding our planet, and how it is changing, is critical for our nation's economy, security, and safety. As individuals, we rely on Earth information in our daily lives for applications ranging from internet mapping and weather forecasting to agricultural

[1] both online at: https://www.nap.edu/catalog/25437

productivity and transportation. These ever-growing capabilities are due in large part to the United States' sustained commitment to satellite-based earth observations.

Satellite observations provide a global perspective of Earth that transforms our scientific understanding of the planet and enables powerful societal applications that help individuals, businesses, the nation, and the world. *The report identifies and prioritizes the science and applications and observations that are needed to understand the dynamic Earth over the next decade.* Pursuing these identified priorities will impact all our lives.

A major component of the Decadal Survey's recommendations included a commitment to a set of observational capabilities to enable substantial progress in all of the following science and applications areas:

- Providing critical information on the make-up and distribution of aerosols and clouds, which in turn improve predictions of future climate conditions and help us assess the impacts of aerosols on human health;
- Addressing key questions about how changing cloud cover and precipitation will affect climate, weather, and Earth's energy balance in the future, advancing understanding of the movement of air and energy in the atmosphere and its impact on weather, precipitation, and severe storms;
- Determining the extent to which the shrinking of glaciers and ice sheets, and their contributions to sea-level rise, is accelerating, decelerating, or remaining unchanged;
- Quantifying trends in water stored on land (e.g., in aquifers) and the implications for issues such as water availability for human consumption and irrigation;
- Understanding alterations to surface characteristics and landscapes (e.g., snow cover, snow melt, landslides, earthquakes, eruptions, urbanization, land-cover and land use) and the implications for applications such as risk management and resource management;
- Assessing the evolving characteristics and health of terrestrial vegetation and aquatic ecosystems, which is important for understanding key consequences such as crop yields, carbon uptake, and biodiversity; and
- Examining movement of land and ice surfaces to determine, in the case of ice, the likelihood of rapid ice loss and significantly accelerated rates of sea-level rise, and in the case of land, changes in strain rates that impact and provide critical insights into earthquakes, volcanic eruptions, landslides, and tectonic plate deformation.

Key issues for Congress regarding the future of space and earth science.

The overarching challenge continues to be how to sustain the baseline and implement the new, critical programs at NASA, NOAA and USGS that are recommended in the Decadal Survey. This will require a combination of continued and perhaps expanded levels of Congressional support, leveraging the emerging opportunities associated with "new space," the commercial sector, and building on the revolution in how data are accessed, managed, and analyzed.

Finally, and most importantly, climate change poses enormous challenges to our way of life and security. The role of earth observations in understanding where and how fast changes will occur, along with informing options for mitigation and adaptation, must be a key element of all observational programs.

What may impact addressing the most compelling scientific questions and opportunities?

Endangered POR components:

PACE mission. PACE (Plankton, Aerosols, Cloud, ocean Ecosystem) is a critical mission for quantifying the role of the ocean ecosystem in the global carbon cycle. When launched, it will give us unprecedented insight into Earth's ocean and atmosphere. Collecting data on these systems is critical to understanding their effects on climate and Earth's habitability. The instruments on PACE will allow for a more detailed understanding of the carbon uptake by the various phytoplankton species. This data will allow scientists and policymakers a stronger position when prioritizing climate change mitigation strategies.

CLARREO-Pathfinder mission. CLARREO-Pathfinder (CPF) is designed to demonstrate in space satellite inter-calibration, traceable to the International Standard of Units. Instrument calibration is essential to providing accurate, well-characterized data. Currently, after launch, instrument scientists often rely on overlapping periods of data from similar sensors, models, evaluating data with collocated in situ observations (when possible), or other suboptimal methods to calibrate satellite instruments. CPF will provide the ability to inter-calibrate instruments in space at accuracies 5 to 10 times beyond current capabilities, allowing them to be combined into accurate data products for weather forecasting and climate modeling. CPF is part of the survey's assumed baseline program of record.

Endangered technological advancements

Continue STEM education. Although one of the richest countries in the world, the U.S. scores in STEM are consistently below average among similar countries. Within the digital world, national borders mostly disappear, and without a competitive and educated workforce the next 'Silicon Valley' could be overseas. Remaining the global leader in technology requires training students in advanced STEM skills.

Enabling Breakthrough Science

The Decadal Survey report stated "Breakthrough science will be done by virtual science teams collaborating through complex, multi-observation data sets," but didn't go farther to explore this as it was determined to be beyond scope. Right now, we are witnessing the rapid, revolutionary transition into a new era in science. Open-source software, cloud data storage, and cloud computing have the potential to enable more widespread and efficient utilization of public data for a myriad of commercial and scientific applications, and new approaches to understanding complex interconnections between our economy, ecosystem, weather, and environment.

The Decadal Survey authors didn't plan for the additional resources needed for a wholesale move of NASA data assets onto the cloud, support for the open source software libraries that underpin rapid scientific advancements and commercial data applications, or how to enable the interdisciplinary science and commercial applications that will subsequently flourish. In my view, this is one example where comparatively small new investments have the potential to deliver outsized benefits. NASA's vast data resources and robust research community make it well-poised to be a global leader in this effort. Jump-starting these activities in NASA could grow the private-public cloud partnership and energize the research community.

There are a couple studies that would help cloud-migration efforts. NASA's data is more than just the observation value, there is also metadata (data about the data) and uncertainty estimates. There are many different approaches to estimate the uncertainty in a measurement, from using artificial intelligence to a careful detailed analysis of how each step contributes to uncertainty. As data moves onto the cloud, the calculation of uncertainty and how it is communicated becomes even more important.

The organization of Federal agencies and funding opportunities directly impact how science is accomplished and can act as either a barrier or enabler for new approaches. A movement of data onto the cloud can easily propagate a 'business as usual' approach to science, but early adopters have found that by removing many of the barriers to data access, how science is accomplished is changing. It changes the type of questions that can be asked, how they are answered, the reproducibility of science, and the dynamic of collaborations. This enables more interdisciplinary research. Capturing all the advantages of cloud computing and open source software will require a re-imagining of how science is organized.

How does CESAS monitor the implementation of the Earth Science Decadal Survey, and what is CESAS's assessment of NASA's progress in implementing the decadal to date?

At twice yearly meetings, NASA is invited to present on their progress and decisions regarding the implementation of the Decadal Survey recommendations.

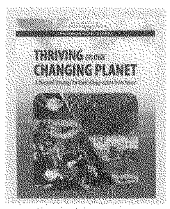
During these presentations, and afterward, there is substantial back-and-forth with CESAS. Afterward, the committee may submit a report to NASA outlining any areas of concern or ask for additional meetings to address specific questions.

NASA is following the Decadal Survey guidance and has as its first priority the completion of the POR. It has also started studies on the implementation of all the recommended "Designated Observables," a program element for Decadal Survey-designated cost-capped medium- and large-size missions to address observables that are *essential* to the program, directed or competed at the discretion of NASA. However, it now appears that implementation of the rest of the recommended program will require appropriations beyond that assumed by the Decadal Survey committee. In particular, additional funds would be needed to initiate the Earth System Explorer line, a new program element involving competitive opportunities for cost-capped medium-size instruments and missions serving specified Decadal Survey-priority observations.

How, if at all, do emerging capabilities in the commercial sector affect the future of earth science and applications?

NASA has contracts with three private companies (Planet, DigitalGlobe, Spire) to buy existing data related to climate variables. These are being evaluated by a broad set of NASA researchers to determine the value of the geophysical information for advancing NASA research and application objectives. These scientists are exploring uses for this data. If these commercial data providers are able to demonstrate products that add value to research and are cost-effective, it will make sense to continue buying and using their data. Yet, in the scientific community, a high level of concern persists about the potential impacts of long term reliance on commercial space companies and loss or internal expertise. At the same time, it is apparent that commercial partners may be more agile and experimental, which impacts possible solutions, cost, and risk.

Emerging capabilities hold promise, but there must be a close collaboration. It is important to consider in detail the design of the data-producing instrument when evaluating data quality. Maximizing data utilization requires close collaboration between data users and data providers, which should begin well before the point when flight data are actually available. Ideally, the engineering process should include the involvement of potential users in the design, development and pre-flight calibration of an instrument. At an absolute minimum, the data users should have access to the detailed engineering design and test results for instruments that measure the data they are buying. This runs into issues of company equipment and security and has the potential to weaken the strength of the average datum used in scientific research.



Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space (2018)

DETAILS

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Summary

This report, *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*, of the National Academies of Sciences, Engineering, and Medicine's 2017-2027 decadal survey for Earth science and applications from space (ESAS 2017) is the second such decadal survey of the National Academies. This summary provides a comprehensive overview of the present decadal survey and its key findings and recommendations; however, readers should note that space limitations do not permit a detailed discussion of each of the report's 17 findings and 20 recommendations.

EARTH OBSERVATION FROM SPACE: A TRANSFORMATIVE CAPABILITY

From the time of the earliest humans, knowledge about Earth has been fundamental to our fate and prospects. Over the past 60 years, particularly rapid progress has been achieved in acquiring such scientific and practical knowledge, due in large part to the special perspective provided by "satellite-based Earth observations."

The vantage point of space enables us to see the extent to which Earth's ever-changing processes influence our lives. These processes operate at local spatial scales, such as the flows of rivers that provide freshwater and the weather and climate conditions that determine crop yields, as well as at global spatial scales, such as changes in the ocean currents that impact commercial fishing and contribute to global change and climate variability. The space-based vantage point also ensures that we can observe processes occurring over a wide range of time scales, from the abrupt (such as earthquakes) to the decadal (such as growth and shrinkage of the world's great ice sheets), and at all time scales in between.

Empowered by this perspective, we are coming to recognize the complex and continually changing ways by which Earth's processes occur, along with the critical roles their observation and understanding play throughout our lives.

Finding 1.1: Space-based Earth observations provide a global perspective of Earth that has

- Over the last 60 years, transformed our "scientific understanding" of the planet, revealing it to be an integrated system of dynamic interactions between the atmosphere, ocean, land, ice, and human society across a range of spatial and temporal scales, irrespective of geographic, political, or disciplinary boundaries.

- In the past decade in particular, enabled "societal applications" that provide tremendous value to individuals, businesses, the nation, and the world. Such applications are growing in breadth and depth, becoming an essential information infrastructure element for society as they are integrated into people's daily lives.

THRIVING ON OUR CHANGING PLANET

This ability to observe our planet comprehensively matters to each of us. Earth information—for use in Internet maps, daily weather forecasts, land-use planning, transportation efficiency, and agricultural productivity, to name a few—is central to our lives, providing substantial contributions to our economies, our national security, and our personal safety. It helps ensure we are a ***thriving*** society.

The Earth information we have come to rely on throughout our daily lives is the result of a sustained commitment to both exploratory and applied Earth science, and to what has become a sophisticated national and international infrastructure of observing systems, scientific research, and applications. A particular strength of the Earth science and applications field is the extent to which curiosity-based science is inextricably integrated with applications-oriented science and societal benefits. Ongoing commitment to this inspirational and practical science has returned benefits to society many times over, and will continue to do so with further support.

Among the most intellectually and practically important revelations from the past 60 years of space-based observation is the extent to which *Earth is **changing**, in multiple ways and for many reasons.* Daily changes, such as weather, were obvious to even the earliest humans, even if not explainable. Longer-term changes, particularly those occurring on global scales, are only now becoming understood and gaining public recognition. Some of these changes are climate related, such as alteration of the El Niño Southern Oscillation (ENSO), but many are not. In addition to climate, changes in air quality, water availability, agricultural soil nutrients, and other Earth resources are being driven largely by human actions. Successfully managing risks and identifying opportunities associated with these changes requires a clear understanding of both the human-driven and the natural processes that underlie them.

A CHALLENGING VISION FOR THE DECADE AND BEYOND

A changing Earth is one we can never understand just from past experience. Its evolving and emerging characteristics must be continually explored through observation. Our scientific curiosity must seek and reveal the new and altered processes that will result from change, if we are to continue applying our knowledge effectively for society's benefit. Decisions we make this decade will be pivotal for predicting the potential for future changes and for influencing whether and how those changes occur. Embracing this new paradigm of understanding a changing Earth, and building a program to address it, is our major challenge for the coming decade and beyond.

Recommendation 2.1: Earth science and applications are a key part of the nation's information infrastructure, warranting a U.S. program of Earth observations from space that is robust, resilient, and appropriately balanced. NASA, NOAA, and USGS, in collaboration with other interested U.S. agencies, should ensure efficient and effective use of U.S. resources by strategically coordinating and advancing this program at the national level, as also recommended in the 2007 Earth Science and Applications from Space (ESAS) decadal survey.

This context of both societal need and intellectual opportunity provided the basis for developing the Earth observation program proposed in this report. Society's fundamental desire to thrive, the expanding scientific knowledge needed to support that desire, and the growing capacity to apply that knowledge are all central motivations for this committee's recommendations. Embracing the goal of understanding Earth in pursuit of this vision—*to thrive on our changing planet*—motivates a new paradigm for the coming decade and beyond.

Earth Science and Applications Paradigm for the Coming Decade

Earth science and derived Earth information have become an integral component of our daily lives, our business successes, and society's capacity to thrive. Extending this societal progress requires that we focus on understanding and reliably predicting the many ways our planet is changing.

A STRUCTURED APPROACH TO ACHIEVING PROGRESS

The next decade is one in which progress will not come easily. Financial and human resource constraints are likely to present challenges to progress (Chapter 1). Succeeding compels NASA, NOAA, and USGS to develop, adopt, and implement strategies to advance both technology and programmatic processes. The committee recommends eight elements (numbered only for identification) of a suggested *strategic framework* (Chapter 2):

1. Commit to sustained science and applications;
2. Embrace innovative methodologies for integrated science/applications;
3. Amplify the cross-benefit of science and applications;
4. Leverage external resources and partnerships;
5. Institutionalize programmatic agility and balance;
6. Exploit external trends in technology and user needs;
7. Expand use of competition; and
8. Pursue ambitious science, despite constraint.

The challenges ahead, and the need for innovative and strategic thinking to overcome them, are reflected in the following community challenge.

Decadal Community Challenge

Pursue increasingly ambitious objectives and innovative solutions that enhance and accelerate the science/applications value of space-based Earth observation and analysis to the nation and to the world in a way that delivers great value, even when resources are constrained, and ensures that further investment will pay substantial dividends.

The committee believes that meeting the challenge described earlier will motivate the scientific community to pioneer *novel approaches* in how it conducts its scientific research, with an emphasis on programmatic and technological innovation to accomplish more with less, with greater attention to the potential benefits of domestic and international partnerships along with the growing capability of commercial sources (Chapters 3 and 4).

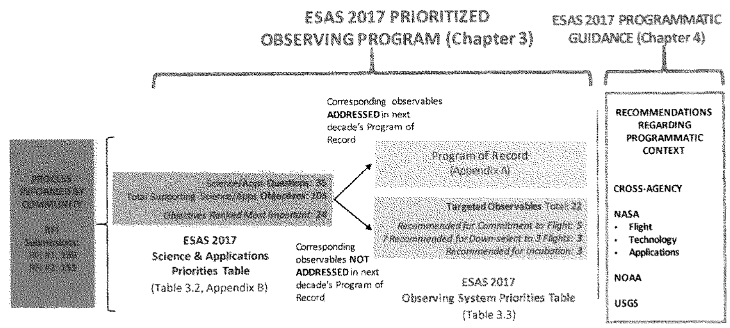

FIGURE S.1 Roadmap for the 2017 Earth Science and Applications from Space (ESAS 2017) decadal survey report based on the survey committee's approach to identifying priorities for the coming decade, starting from community requests for information (RFIs), refining this input to determine priority science and applications questions and objectives, and then identifying new observing system priorities (assuming completion of the program of record). These priorities are complemented by programmatic recommendations.

The committee conducted its work in close collaboration with the decadal survey's five study panels, each interdisciplinary and together spanning all of the disciplines associated with Earth system science. The survey process is summarized in Figure S.1. It was designed to converge—from a large number of community-provided possibilities—to a final, small set of Science and Applications Priorities (shown in blue) and Observing System Priorities (shown in green) that are required to address the nation's Earth science and applications needs. *This process assumed that the existing and planned instruments in the Program of Record (POR) are implemented as expected.*

ESTABLISHING SCIENCE AND APPLICATIONS PRIORITIES

Starting from an initial set of 290 community-submitted ideas, the five interdisciplinary panels, and then the committee narrowed this large set of ideas to a set of *35 key Earth science and applications questions* to be addressed over the next decade. Together, these questions comprehensively address those areas for which advances are most needed in both curiosity-driven and practically focused Earth science and the corresponding practical uses of Earth information. To identify the observational capabilities required to answer these questions, the committee then defined a set of underlying science and applications objectives, evaluating and assigning each to one of three prioritization categories: Most Important (MI), Very Important (VI), and Important (I).

This process informed the committee's Recommendation 3.1 that NASA, NOAA, and USGS pursue the key science and applications questions summarized in Table S.1 (and described in more detail in the body

TABLE S.1 Science and Applications Priorities for the Decade 2017-2027 (see note following table for description)

Science and Applications Area	Science and Applications Questions Addressed by Most Important Objectives
Coupling of the Water and Energy Cycles	**(H-1)** How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods? **(H-2)** How do anthropogenic changes in climate, land use, water use, and water storage interact and modify the water and energy cycles locally, regionally, and globally, and what are the short- and long-term consequences?
Ecosystem Change	**(E-1)** What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space? **(E-2)** What are the fluxes (of carbon, water, nutrients, and energy) *between* ecosystems and the atmosphere, the ocean, and the solid Earth, and how and why are they changing? **(E-3)** What are the fluxes (of carbon, water, nutrients, and energy) *within* ecosystems, and how and why are they changing?
Extending and Improving Weather and Air Quality Forecasts	**(W-1)** What planetary boundary layer (PBL) processes are integral to the air-surface (land, ocean, and sea ice) exchanges of energy, momentum, and mass, and how do these impact weather forecasts and air quality simulations? **(W-2)** How can environmental predictions of weather and air quality be extended to seamlessly forecast Earth system conditions at lead times of 1 week to 2 months? **(W-4)** Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do? **(W-5)** What processes determine the spatiotemporal structure of important air pollutants and their concomitant adverse impact on human health, agriculture, and ecosystems?
Reducing Climate Uncertainty and Informing Societal Response	**(C-2)** How can we reduce the uncertainty in the amount of future warming of the Earth as a function of fossil fuel emissions, improve our ability to predict local and regional climate response to natural and anthropogenic forcings, and reduce the uncertainty in global climate sensitivity that drives uncertainty in future economic impacts and mitigation/adaptation strategies?
Sea-Level Rise	**(C-1)** How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage? **(S-3)** How will local sea level change along coastlines around the world in the next decade to century?
Surface Dynamics, Geological Hazards, and Disasters	**(S-1)** How can large-scale geological hazards be accurately forecasted in a socially relevant time frame? **(S-2)** How do geological disasters directly impact the Earth system and society following an event? **(S-4)** What processes and interactions determine the rates of landscape change?

Very Important (Summarized)	Important (Summarized)
(H-4) Influence of water cycle on natural hazards and preparedness **(W-3)** Influence of Earth surface variations on weather and air quality **(C-3)** Impacts of carbon cycle variations on climate and ecosystems **(C-4)** Earth system response to air-sea interactions **(C-5)** Impact of aerosols on global warming **(C-6)** Improving seasonal to decadal climate forecasts **(C-7)** Changes in decadal scale atmospheric/ocean circulation and impacts **(C-8)** Consequence of amplified polar climate change on Earth system	**(H-3)** Freshwater availability and impacts on ecosystems/society **(W-6)** Long-term air pollution trends and impacts **(W-7)** Processes influencing tropospheric ozone and its atmospheric impacts **(W-8)** Methane variations and impacts on tropospheric composition and chemistry **(W-9)** Cloud microphysical property dependence on aerosols and precipitation **(W-10)** Cloud impacts on radiative forcing and weather predictability **(E-4)** Quantifying carbon sinks and their changes **(E-5)** Stability of carbon sinks

TABLE S.1 Continued

Very Important (Summarized)	Important (Summarized)
(S-5) How energy flows from the core to Earth's surface **(S-6)** Impact of deep underground water on geologic processes and water supplies	**(C-9)** Impacts of ozone layer change **(S-7)** Improving discovery of energy, mineral, and soil resources

NOTE: The highest-priority questions (defined as those associated with Most Important objectives) are listed in full; other questions associated with Very Important or Important objectives are briefly summarized. No further priority is assumed within categories, and the topics are listed alphabetically. Letter and number combinations in parentheses refer to the panel (H = Hydrology, W = Weather, E = Ecosystems, C = Climate, S = Solid Earth) and the numbering of each panel's questions. Complete versions of this table are provided in Table 3.2 and in Appendix B.

of the report; complete versions of this table are provided in Table 3.2 and Appendix B). These questions address the central science and applications priorities for the coming decade.

Recommendation 3.1: NASA, NOAA, and USGS, working in coordination, according to their appropriate roles and recognizing their agency mission and priorities, should implement an integrated programmatic approach to advancing Earth science and applications that is based on the *questions and objectives* listed in Table 3.2, "Science and Applications Priorities for the Decade 2017-2027."

By pursuing these priorities, important advances will be made in areas that are both scientifically challenging and of direct impact to how we live. A major component of the committee's observing program recommendations is a commitment to a set of observation capabilities, outlined in the next section that will enable substantial progress in all of the following science and applications areas:

- Providing critical information on the *make-up and distribution of aerosols and clouds,* which in turn improve predictions of future climate conditions and help us assess the impacts of aerosols on human health;
- Addressing key questions about how *changing cloud cover and precipitation* will affect climate, weather, and Earth's energy balance in the future, advancing understanding of the movement of air and energy in the atmosphere and its impact on weather, precipitation, and severe storms;
- Determining the extent to which the *shrinking of glaciers and ice sheets,* and their contributions to sea-level rise, is accelerating, decelerating, or remaining unchanged;
- Quantifying *trends in water stored on land* (e.g., in aquifers) and the implications for issues such as water availability for human consumption and irrigation;
- Understanding *alterations to surface characteristics and landscapes* (e.g., snow cover, snowmelt, landslides, earthquakes, eruptions, urbanization, land-cover, and land use) and the implications for applications such as risk management and resource management;
- Assessing the *evolving characteristics and health of terrestrial vegetation and aquatic ecosystems,* which is important for understanding key consequences such as crop yields, carbon uptake, and biodiversity; and
- Examining *movement of land and ice surfaces* to determine, in the case of ice, the likelihood of rapid ice loss and significantly accelerated rates of sea-level rise, and in the case of land, changes in strain rates that impact and provide critical insights into earthquakes, volcanic eruptions, landslides, and tectonic plate deformation.

In addition, the committee is proposing competitive observational opportunities, also outlined in the next section, to address at least three of the following science and applications areas:

- Understanding the *sources and sinks of carbon dioxide and methane* and the processes that will affect their concentrations in the future;
- Understanding *glacier and ice sheet contributions to rates of sea-level rise* and how they are likely to impact sea-level rise in the future;
- Improving understanding of *ocean circulation*, the exchanges between the ocean and atmosphere, and their impacts on weather and climate;
- Assessing *changes in ozone and other gases* and the associated implications for human health, air quality, and climate;
- Determining the *amount and melt rates of snow* and the associated implications for water resources, weather, climate, flooding, drought, and so on;
- Quantifying biomass and characterizing ecosystem structure to assess *carbon uptake from the atmosphere and changes in land cover* and to support resource management; and
- Providing critical insights into the *transport of pollutants, wind energy, cloud processes, and how energy moves* between the land or ocean surfaces and the atmosphere.

The recommended program will advance scientific knowledge in areas that are ripe for discovery and that have direct impact on the way we live today. The knowledge developed in the coming decade, through this science, holds great promise for informing actions and investments for a successful future.

IMPLEMENTING AN INNOVATIVE OBSERVING PROGRAM

Addressing the committee's priority science and applications questions requires an ongoing commitment to existing and planned instruments and satellites in the POR. The committee's recommended observing program builds from this, filling gaps in the POR where observations are needed to address the key science and applications objectives for the coming decade. This observing program is summarized in Table S.2 (Table 3.3 in Chapter 3) and in the accompanying Recommendation 3.2. Most observables are allocated to two new NASA flight program elements: a committed group of observations termed "Designated," along with a competed group termed "Earth System Explorer." Within these two new flight program elements, eight of the priority observation needs from Table S.2 are expected to be implemented as instruments, instrument suites, or missions. In addition, several observables are assigned to a new program element called "Incubation," intended to accelerate readiness of high-priority observables not yet feasible for cost-effective flight implementation. Finally, an expansion of the Venture program is proposed for competed small missions to add a focus on continuity-driven observations. Together, these new program elements complement existing NASA flight program elements such as the Venture program.

The foundational observations in Table S.2—the five shown in the "Designated" column that are recommended specifically by the committee for implementation, and the three to be competitively selected from among the identified set of seven "Earth System Explorer" candidates—augment the existing POR and ensure that the survey's 35 priority science and applications questions can be effectively addressed, to the extent that resources allow. In keeping with the study's statement of task, specific missions and instruments were not identified, ensuring that the sponsoring agencies will have discretion for identifying the most cost-effective and appropriate space-based approaches to implementing the recommended set of observations. Each of the new NASA flight program elements promises innovative means for using

TABLE S.2 Observing System Priorities (see note following table for description)

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated	Explorer	Incubation
Aerosols	*Aerosol properties, aerosol vertical profiles, and cloud properties* to understand their effects on climate and air quality	Backscatter lidar and multichannel/multiangle/polarization imaging radiometer flown together on the same platform	X		
Clouds, Convection, and Precipitation	*Coupled cloud-precipitation state and dynamics* for monitoring global hydrological cycle and understanding contributing processes including cloud feedback	Dual-frequency radar, with multifrequency passive microwave and sub-mm radiometer	X		
Mass Change	*Large-scale Earth dynamics* measured by the changing mass distribution within and between the Earth's atmosphere, oceans, groundwater, and ice sheets	Spacecraft ranging measurement of gravity anomaly	X		
Surface Biology and Geology	*Earth surface geology and biology*, ground/water temperature, snow reflectivity, active geologic processes, vegetation traits, and algal biomass	Hyperspectral imagery in the visible and shortwave infrared (IR), multi- or hyperspectral imagery in the thermal IR	X		
Surface Deformation and Change	*Earth surface dynamics* from earthquakes and landslides to ice sheets and permafrost	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction	X		
Greenhouse Gases	*CO_2 and methane fluxes and trends*, global and regional with quantification of point sources and identification of sources and sinks	Multispectral shortwave IR and thermal IR sounders; or lidar*		X	
Ice Elevation	*Global ice characterization* including elevation change of land ice to assess sea-level contributions and freeboard height of sea ice to assess sea ice/ocean/atmosphere interaction	Lidar*		X	
Ocean Surface Winds and Currents	*Coincident high-accuracy currents and vector winds* to assess air-sea momentum exchange and to infer upwelling, upper ocean mixing, and sea-ice drift	Doppler scatterometer		X	
Ozone and Trace Gases	*Vertical profiles of ozone and trace gases* (including water vapor, CO, NO_2, methane, and N_2O) globally and with high spatial resolution	UV/VIS/IR microwave limb/nadir sounding and UV/VIS/IR solar/stellar occultation		X	
Snow Depth and Snow Water Equivalent	*Snow depth and snow water equivalent*, including high spatial resolution in mountain areas	Radar (Ka/Ku band) altimeter; or lidar*		X	
Terrestrial Ecosystem Structure	*3D structure of terrestrial ecosystem* including forest canopy and aboveground biomass and changes in aboveground carbon stock from processes such as deforestation and forest degradation	Lidar*		X	
Atmospheric Winds	*3D winds in troposphere/planetary boundary layer (PBL)* for transport of pollutants/carbon/aerosol and water vapor, wind energy, cloud dynamics and convection, and large-scale circulation	Active sensing (lidar, radar, scatterometer); or passive imagery or radiometry-based atmospheric motion vectors (AMVs) tracking; or lidar*		X	X

TABLE S.2 Continued

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated	Explorer	Incubation
Planetary Boundary Layer	*Diurnal 3D PBL thermodynamic properties and 2D PBL structure* to understand the impact of PBL processes on weather and air quality through high vertical and temporal profiling of PBL temperature, moisture, and heights	Microwave, hyperspectral IR sounder(s) (e.g., in geo or small sat constellation), GPS radio occultation for diurnal PBL temperature and humidity and heights; water vapor profiling DIAL lidar; and lidar* for PBL height			X
Surface Topography and Vegetation	*High-resolution global topography*, including bare surface land topography, ice topography, vegetation structure, and shallow water bathymetry	Radar; or lidar*			X

* Could potentially be addressed by a multifunction lidar designed to address two or more of the Targeted Observables

Other ESAS 2017 Targeted Observables, Not Allocated to a Flight Program Element

Aquatic-Coastal Biogeochemistry	Radiance Inter-calibration	Surface Water Height
Magnetic Field Changes	Salinity	
Ocean Ecosystem Structure	Soil Moisture	

NOTE: Observations (Targeted Observables) identified by the steering committee as needed in the coming decade, beyond what is in the Program of Record, allocated as noted in the last three columns (and color-coded) to three new NASA flight program elements (*Designated, Earth System Explorer, Incubation*; as defined in the accompanying text). Within categories, the targeted observables are listed alphabetically. Targeted Observables included in the original priority consideration but not allocated to a program element are listed at the bottom of the table (see Appendix C for a complete summary).

competition and other programmatic tools to increase the cadence and quality of flight programs, while optimizing cost and risk.

Recommendation 3.2: NASA should implement a set of space-based observation capabilities based on this report's proposed program (which was designed to be affordable, comprehensive, robust, and balanced) by implementing its portion of the Program of Record and adding observations described in Table 3.3, "Observing System Priorities." The implemented program should be guided by the budgetary considerations and decision rules contained in this report and accomplished through five distinct program elements:

1. ***Program of Record.* The series of existing or previously planned observations, which must be completed as planned. Execution of the ESAS 2017 recommendation requires that the total cost to NASA of the Program of Record flight missions from fiscal year (FY) 2018 through FY 2027—October 1, 2017 through September 30, 2027—be capped at $3.6 billion.**
2. ***Designated.* A program element for ESAS-designated cost-capped medium- and large-size missions to address observables essential to the overall program, directed or competed at the discretion of NASA.**
3. ***Earth System Explorer.* A *new* program element involving competitive opportunities for cost-capped medium-size instruments and missions serving specified ESAS-priority observations.**

4. ***Incubation.*** **A *new* program element, focused on investment for priority observation capabilities needing advancement prior to cost-effective implementation, including an innovation fund to respond to emerging needs.**
5. ***Earth Venture.*** **Earth Venture program element, as recommended in ESAS 2007, with the addition of a *new* Venture-continuity component to provide opportunity for low-cost sustained observations.**

The committee is confident, based on analyses of technical readiness and cost performed during the study, that the recommended observations have feasible implementations that can be accomplished on schedule and within the stated cost caps. The proposed program was designed both to fit within anticipated budgets (assumed for the purposes of this report to grow only with inflation) and to ensure balance in the mission portfolio among program elements (Figure S.2). As appropriate, candidate instruments and missions were formally subjected to a Cost Assessment and Technical Evaluation (CATE) to assess budget needs. The committee considered management of development cost to be of critical importance to effective implementation of this program, in order to avoid impacting other programs and altering the desired programmatic balance. Should budgets be more or less than anticipated, the report includes decision rules for altering plans in a manner that seeks to ensure the overall program integrity.

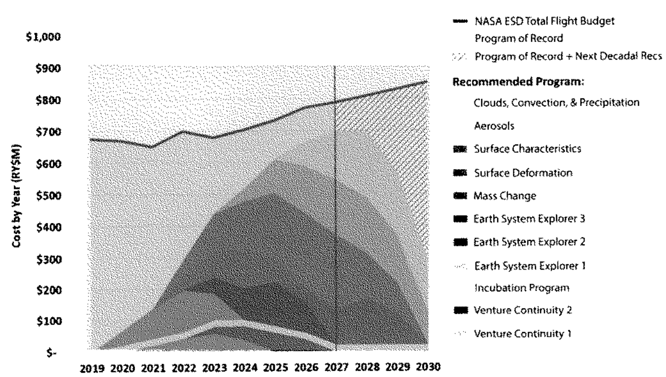

FIGURE S.2 The 2017 Earth Science and Applications from Space (ESAS 2017) real-year dollar estimated costs (colored wedges), broken down by NASA flight program element proposed in this report, as compared to the anticipated flight budget (black line), showing how the ESAS 2017 costs fit within the available $3.4 billion budget through 2027. The total NASA budget for flight elements assumes growth at the rate of inflation for years beyond the current budget projection. Only the investments related to ESAS 2017 recommendations are shown. The gap between the estimated costs and the available budget represents funds that have been committed to other non-ESAS mission-related activities.

ENABLING THE PROGRAM

Finally, none of this happens without "robust supporting programs" at NASA, NOAA, and USGS that provide the enabling resources for developing the recommended space-based observing systems and evaluating the data they produce. In particular, these supporting programs are central to transforming scientific advances into applications and societal benefits. The committee has proposed a variety of programmatic actions intended to improve the ability of each agency to deliver on its space-based observation programs.

Key among these are findings and recommendations associated with the following: ensuring balanced and robust programmatic structures (Findings 4.4 and 4.5); recognizing the importance of sustained land imaging through the USGS Landsat program (Finding 4.10); and leveraging partnering opportunities (such as the European Union's Copernicus/Sentinel program noted in Recommendation 4.5) that enhance operational efficiencies and ensure that the agencies can accomplish the most possible within their available resources (Finding 4.10; Recommendations 4.5, 4.11, and 4.12).

Finding 4.4: A robust and resilient Earth Science Division (ESD) program has the following attributes:

- A healthy cadence of small/medium missions to provide the community with regular flight opportunities, to leverage advances in technologies and capabilities, and to rapidly respond to emerging science needs;
- A small number of large cost-constrained missions, whose implementation does not draw excessive resources from smaller and more frequent opportunities;
- Strong partnerships with U.S. government and non-U.S. space agencies;
- Complementary programs for airborne, in situ, and other supporting observations;
- Periodic assessment of the return on investment provided by each program element; and
- A robust mechanism for trading the need for continuity of existing measurement against new measurements.

Finding 4.5: Maximizing the success of NASA's Earth science program requires balanced investments across its program elements, each critically important to the overall program. The *flight* program provides observations that the *research and analysis* program draws on to perform scientific exploration, the *applied sciences* program transforms the science into real-world benefits, and the *technology* program accelerates the inclusion of technology advances in flight programs. The current balance across these four program elements is largely appropriate, enabling a robust and resilient Earth science program, and can be effectively maintained using decision rules such as recommended in this report. Some adjustment of balance within each program element is warranted, as recommended in this report.

Finding 4.10: Extension of Landsat capability through synergy with other space-based observations opens new opportunities for Landsat data usage, as has been demonstrated with the European Space Agency (ESA) through cross-calibration and data sharing for Sentinel-2. These successes serve as a model for future partnerships and further synergies with other space-based observations.

Recommendation 4.5: Because expanded and extended international partnerships can benefit the nation:

- **NASA should consider enhancing existing partnerships and seeking new partnerships when implementing the observation priorities of this decadal survey.**
- **NOAA should strengthen and expand its already strong international partnerships, by (1) coordinating with partners to further ensure complementary capabilities and operational backup while**

minimizing unneeded redundancy; and (2) extending partnerships to the more complete observing system life cycle that includes scientific and technological development of future capabilities.
- **USGS should extend the impact of the Sustainable Land Imaging (SLI) program through further partnerships such as that with the European Sentinel program.**

Recommendation 4.11: NOAA should establish itself among the leading government agencies that exploit potential value of commercial data sources, assessing both their benefits and risks in its observational data portfolio. It should innovate new government/commercial partnerships as needed to accomplish that goal, pioneer new business models when required, and seek acceptable solutions to present barriers such as international partner use rights. NOAA's commercial data partnerships should ensure access to needed information on data characteristics and quality as necessary and appropriate, and be robust against loss of any single source/provider if the data are essential to NOAA core functions.

Recommendation 4.12: NOAA should establish, with NASA, a flexible framework for joint activities that advance the capability and cost-effectiveness of NOAA's observation capabilities. This framework should enable implementation of specific project collaborations, each of which may have its own unique requirements, and should ensure (1) clear roles, (2) mutual interests, (3) life-cycle interaction, (4) multidisciplinary methodologies, (5) multielement expertise, and (6) appropriate budget mechanisms.

ANTICIPATED PROGRESS WITHIN THE DECADE

In this report, the committee identifies the science and applications, observations, and programmatic support needed to bring to fruition its vision of understanding deeply the nature of our changing planet. With implementation of its recommended plan, the committee expects the following to have been accomplished by the end of the survey decade:

Programmatic implementation within the agencies will be made more efficient by
- *Increasing Program Cost-Effectiveness.* Promote expanded competition with medium-size missions to take better advantage of innovation and leveraged partnerships.
- *Institutionalizing Sustained Science Continuity.* Establish methods to prioritize and facilitate the continuation of observations deemed critical to monitoring societally important aspects of the planet, after initial scientific exploration has been accomplished.
- *Enabling Untapped NASA-NOAA Synergies.* Establish more effective means for NASA-NOAA partnership to jointly develop the next generation of weather instruments, accelerating NOAA's integration of advanced operational capabilities.

Improved observations will enable exciting new science and applications by
- *Initiating or Deploying More Than Eight New Priority Observations of Our Planet.* Develop or launch missions and instruments to address new or extended priority observation areas that serve science and applications. Five are prescribed in the committee's recommended program for NASA, and three are to be chosen from among seven candidate areas prioritized by the committee to form the basis of a new class of NASA competed medium-size missions. These new observation priorities will be complemented by an additional two new small missions and six new instruments to be selected through NASA's existing Earth Venture program element, and two opportunities for sustained observations to be selected through the new Venture-Continuity strand of this program. The existing and planned POR will also be implemented as expected.

- *Achieving Breakthroughs on Key Scientific Questions.* Advance knowledge throughout portions of the survey's 35 key science questions (Table S.1, above) that address critical unknowns about the Earth system and promise new societal applications and benefits.

Businesses and individuals will receive enhanced value from scientific advances and improved Earth information, such as

- *Increased Benefits to Operational System End-Users.* Enhanced processes and tools to leverage lost-cost commercial and international space-based observations will allow NOAA and USGS to have greater impact on the communities they serve.
- *Accelerated Public Benefits of Science.* Improved capacity for transitioning science to applications will make it possible to more quickly and effectively achieve the societal benefits of scientific exploration, generating applications more responsive to evolving societal needs.
- *Development of Innovative Commercial Applications.* New observations and data products enable innovative commercial applications that have the potential for substantial economic benefit to both developers and end users.

Building on the success and discoveries of the past several decades, this report's balanced program provides a pathway to realizing remarkable scientific and societal benefits from space-based Earth observations. It ensures that the United States will *continue to be a visionary leader and partner* in Earth observation over the coming decade, inspiring the next generation of Earth science and applications innovation and the people who make that possible.

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Dr. Gentemann is a Senior Scientist at Earth and Space Research, a nonprofit research institute located in Seattle, Washington, an Affiliate at the University of Washington Applied Physics Laboratory, Co-Chair of the National Academies of Sciences, Engineering, and Medicine (NASEM) Standing Committee on Earth Science and Applications from Space (CESAS), and acting Chair of NOAA's Science Advisory Board's Data Archive and Access Requirements Working Group. Her more recent research focuses on interdisciplinary science using cloud computing, open source software development, machine learning for applications and algorithm development using remote sensing data, air-sea interactions, and upper ocean physical processes. She has worked on the calibration, radiative transfer modeling, algorithm development, validation, and operational near-real-time distribution of multiple satellite passive microwave sensor data.

She received a B.S. from Massachusetts Institute of Technology, an M.S. in Physical Oceanography from Scripps Institution of Oceanography, and a Ph.D. in Meteorology and Physical Oceanography from the University of Miami. She has served on many national and international science teams, working groups, and committees for NASA, NOAA, AGU, JAXA, and the National Academies of Sciences, Medicine, and Engineering (NASEM). In 2013, she received the American Geophysical Union Charles S. Falkenberg Award, for a "scientist under 45 years of age who has contributed to the quality of life, economic opportunities, and stewardship of the planet through the use of Earth science information and to the public awareness of the importance of understanding our planet." In 2008, she was the principal investigator of the Multi-sensor Improved Sea Surface Temperature (MISST) Project that received the National Oceanographic Partnership Program Excellence in Partnering Award. In 2001, she was part of the Satellite Ocean Atlas Team that was awarded the NASA Group Achievement Award for outstanding achievement in the utilization of multiple observations from space for the study of the global oceans.

She has led 4 large academic, governmental, commercial partnerships, coordinating with over 20 scientists on each project, served on and chaired numerous international and national science teams, working groups, and committees. She currently has 43 papers published and is a member of the American Geophysical Union (AGU), American Meteorological Society (AMS), and IEEE Geoscience and Remote Sensing Society.

Chairwoman HORN. Thank you, Dr. Gentemann. Dr. Spergel.

TESTIMONY OF DR. DAVID SPERGEL, CHARLES YOUNG PROFESSOR OF ASTRONOMY, PRINCETON UNIVERSITY, AND DIRECTOR, CENTER FOR COMPUTATIONAL ASTROPHYSICS, FLATIRON INSTITUTE, AND FORMER CHAIR, SPACE STUDIES BOARD, NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE

Dr. SPERGEL. I want to thank Chairwoman Horn and the Committee for this opportunity to speak. I'm David Spergel, a Princeton Professor, Director of the Center for Computational Astrophysics, and the past Chair of the Space Studies Board. While these experiences inform my testimony, these views are my own.

Many of NASA's most important activities from Mars exploration to studying extrasolar planets to understanding the cosmos are centuries-long projects, the modern version of the construction of the great medieval cathedrals. The decadal surveys provide blueprints for constructing these cathedrals, and NASA science has thrived by being guided by these plans.

Monitoring our rapidly changing planet is both a great scientific challenge and a pressing societal need. "Thriving on a Changing Planet: A Decadal Strategy for Earth Observations from Space" identifies the highest priority study areas, the most important observables, and recommends structuring new NASA missions accordingly. I want to reinforce Dr. Gentemann's comments and urge the Committee to charge NASA to implement these priorities. Addressing climate change begins with deepening our understanding of Earth.

The search for life is another grand challenge. Within our own solar system, we have learned that water is everywhere. Comets bring water to the Moon and to Mercury. Mars not only has a wet past but still has liquid water today. Outer planet moons such as Europa host vast oceans beneath their icy shells, a discovery that suggests new potential habitable destinations. Did any of these systems once host life? Do they host life today?

To answer these questions, NASA is in the midst of a set of interlocking missions exploring the red planet. As outlined in the Planetary Decadal Survey, the Mars 2020 mission is the next step in this program, culminating with the return of carefully selected samples from Mars. NASA's also making progress in building the Europa Clipper. The Planetary Decadal Survey, however, did not identify a major investment in studying the lifeless Moon as one of its highest priorities. I'm concerned that high-priority SMD programs will be terminated to enable lower-priority science and accelerating the lunar program.

Understanding the dominant component of our universe, dark energy, is another grand challenge. Both Europe and China are leading missions to study it. Fortunately, enabled by congressional support, NASA continues to move forward with WFIRST, the Astronomy Decadal's top priority dark energy mission. As Co-Chair of its science team, I'm happy to say that WFIRST is meeting its technical requirements and is on track for a 2025 launch and on budget.

Now, all of these missions are enabled by technology developed both internally within NASA and by external advances. Regrettably, the Space Technology Mission Directorate is reducing these long-term investments for its future science missions and is focusing its resources toward the short-term goal of Moon 2024. This is eating the seed corn of future projects.

New commercial advances are offering NASA new opportunities for innovation. The desire to build self-driving cars advances autonomous systems. The machine-learning revolution provides novel tools both for analyzing Facebook images and NASA images. GPUs (graphics processing units) are now pushing high-performance computing hardware. Open-code development is driving innovation across industry and academia. NASA and the science community needs to be open to these new innovation sources.

While NASA does face immediate challenges like successfully completing and launching JWST, this is an incredibly exciting time for science. NASA satellites have discovered thousands of exoplanets and detected the brilliant flash from the merger of two neutron stars. NASA has launched a satellite that will literally touch the sun. NASA's exploration of our solar system is revealing new insights into our origins. Its satellite observations are deepening our understanding of the rapidly changing Earth. Most importantly, each of these discoveries raises new questions that drive science forward. These discoveries were enabled by an agency guided by the community science priorities through the decadal surveys, and I urge you to continue to let these surveys guide our science programs.

Thank you.

[The prepared statement of Dr. Spergel follows:]

Statement of David N. Spergel

I thank Chairwoman Horn, Ranking Member Babin and other committee members for the opportunity to testify on NASA's science program. My name is David Spergel. I am Charles Young Professor of Astronomy on the Class of 1897 Foundation at Princeton University and Director of the Center for Computational Astrophysics at the Flatiron Institute, a new institute funded by the Simons Foundation to conduct basic research in computational sciences. I am also a past chair of the Space Studies Board, serve on the JPL advisory board, and am currently co-chair of the WFIRST Formulation Science Working Group. While these experiences inform my testimony, these views are my own.

Our multi-generational program of exploring and studying space is the modern version of the construction of the great medieval cathedrals of Europe. Many of NASA's most important activities from sending humans to Mars to studying extrasolar planets to understanding the cosmos are century-long projects.

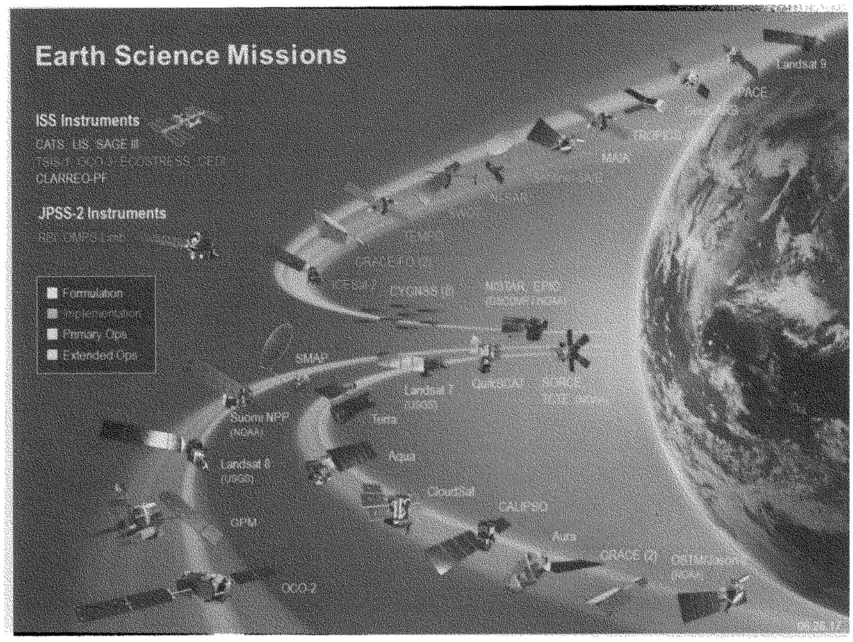
For the NASA Science Mission Directorate, the National Academies' decadal survey process provides a blueprint for constructing these cathedrals. They bring together an entire community to create a vision for each subfield. The Science Mission Directorate has been effective at implementing these plans and launching missions that produce transformative science. As chair of the International Astronomical Union's committee on international collaboration, I see how other nations look to our decadal process and the interactions between the Federal government and the Academies as a model. I have been consulted by colleagues from Canada, New Zealand and India on how to implement their own processes. Both Europe and Japan have developed their own version of the decadal process modelled on the Academies' reports.

Understanding our rapidly changing planet is perhaps NASA's greatest scientific challenge and a pressing societal need. As the recent NAS report, "Thriving on a Changing Planet: A Decadal Strategy for Earth Observation from Space" finds:

> Space-based Earth observations provide a global perspective of Earth that has
>
> - over the last 60 years, transformed our *scientific understanding* of the planet, revealing it to be an integrated system of dynamic interactions between the atmosphere, ocean, land, ice, and human society across a range of spatial and temporal scales, irrespective of geographic, political, or disciplinary boundaries.
> - In the past decade in particular, enabled *societal applications* that provide tremendous value to individuals, businesses, the nation, and the world. Such applications are growing in breadth and depth, becoming an essential information infrastructure element for society as they are integrated into people's daily lives.

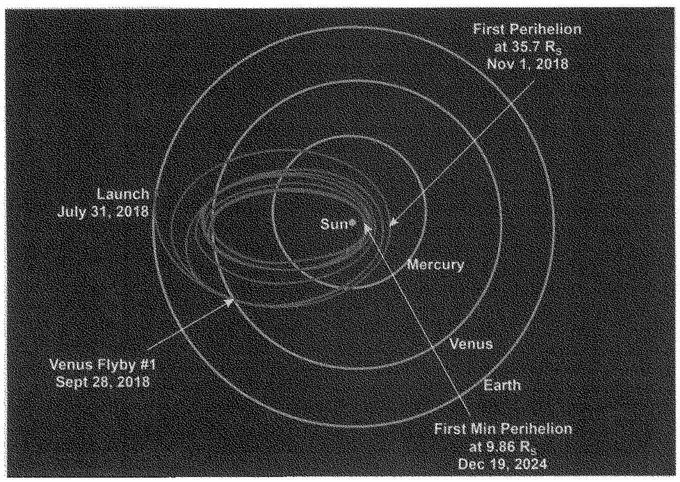
Monitoring the Earth from space requires a robust, resilient and appropriately balanced constellation of satellites that will provide the observational capacity to address our most profound problems.

"Thriving on Our Changing Planet" identified six main categories for study: the coupling of the water and energy cycles, ecosystem change, extending and improving weather and air quality forecasts, sea level rise, reducing climate uncertainty and informing societal response and surface dynamics, geological hazards and disasters. The report recommended augmenting the program of record with eight priority observables and recommended structuring new NASA missions to address these areas of study. They also recommended ways in which NOAA and USGS can leverage NASA investment in these capabilities. I hope that as this committee considers reauthorizing NASA that it will charge the agency to implement these decadal priorities.



Earth scientists utilize a large constellation of current and planned missions to monitor the changing planet. NASA image

Understanding the physics of our Sun and the many ways that it affects the space environment and the Earth itself is another one of NASA's grand challenges. What is the origin of the Sun's activity? How does this affect the space environment, the solar system and the Earth itself? These questions are not only profound physics questions but have important economic consequences as space weather could devastate our technological society. Last year, NASA launched the Parker Solar Probe, an ambitious mission that will effectively touch the Sun and directly probe the origin of Solar activity. My Princeton colleague Dave McCommas is leading the next heliophysics mission, the Interstellar Mapping and Acceleration Probe. IMAP will help researchers better understand the boundary of the heliosphere, the magnetic bubble surrounding and protecting our solar system. The DRIVE initiative is an important complement to these major missions: a combination of cubesats, small sats, and theoretical work. Both pieces are needed for a healthy space science program.



The Parker Solar Probe is enroute to the Sun. It will pass far closer to the Sun than any other satellite. Parker Solar Probe will study the origin of the Sun's activity. NASA image

Within our own solar system, we have learned that water, the most essential ingredient for life is seemingly ubiquitous in our solar system. Comets have brought water to burning hot Mercury and the seemingly barren Moon. Mars had not only a wet past but as recent observations reveal has liquid water. Outer planet moons such as Europa host vast oceans beneath their icy shells, a discovery that suggests new potential habitable destinations. Did any of these systems once host life? Do they still host life today?

The exploration of Mars is another one of humanity's multi-generational challenges being addressed with NASA's Mars program with a set of interlocked missions exploring the Red Planet. The Mars 2020 mission is the next step in this program culminating with the return of carefully selected samples. As the NAS report "Vision and Planetary Sciences in the Decade 2013-2022" recommends:

> Mars is unique among the planets in having experienced processes comparable to those on Earth during its formation and evolution. Crucially, the martian surface preserves a record of earliest solar system history, on a planet with conditions that may have been similar to those on Earth when life emerged. It is now possible to select a site on Mars from which to collect samples that will address the question of whether the planet was ever an abode of life.

Besides the enormous scientific value of the samples, the process of sample return should be an important step towards NASA's horizon goal of sending humans to Mars and returning them safely to Earth.

NASA is also making progress in building the planetary science decadal survey other priority mission, the Europa Clipper. Europa is one of the most fascinating objects in the Solar system with its deep oceans, underwater vents, and the tantalizing possibility that it might host life.

Neither the planetary science decadal survey nor its more recent mid-decadal report have identified a major investment in lunar science as one of the highest priorities of the planetary science community. Speaking as an individual and as a reader of the various community decadal reports, I am concerned by the potential reallocation of resources from the top priorities of the scientific communities towards the lunar program. In its recent report, the National Academies' Committee on Astrobiology and Planetary Sciences' *Review of the Planetary Science Aspects of NASA SMD's Lunar Science and Exploration Initiative* noted,

> The program as currently formulated, while aligned with decadal priorities, does not, however, replace the lunar science priorities and missions recommended in *Vision and Voyages*, the latter of which remain competitive in the New Frontiers class. It remains the responsibility of the next planetary science decadal survey to evaluate these missions as well as the planetary science aspects of the Lunar Discovery and Exploration Program in the context of the planetary program.

I am concerned that high priority programs in Earth Science, Heliophysics, and Astrophysics could be terminated so to enable projects that were not identified as decadal priorities in the planetary science program.

The Event Horizon Telescope's image of an accretion disk is the most compelling astronomical image of the year. While the image is a triumph of a long-term NSF-funded project, its scientific value rests on the synergies of Earth-based and space-based measurements. By combining the Hubble Telescope's image of its powerful jet, the radio interferometric measurements of M87's central ring, and NASA's *Chandra* and *NuSTAR* measurements of the X-ray luminosity, astronomers have been able to infer the presence of supermassive rotating black hole. Similarly, the combination of LIGO's detection of a neutron star-neutron star merger and *SWIFT*'s detection of its electromagnetic counterpart has led astronomers to an understanding of both the origin of gold and platinum and one of the most powerful tests of alternatives to general relativity. These discoveries demonstrate the power of multi-wavelength and multi-messenger astronomy.

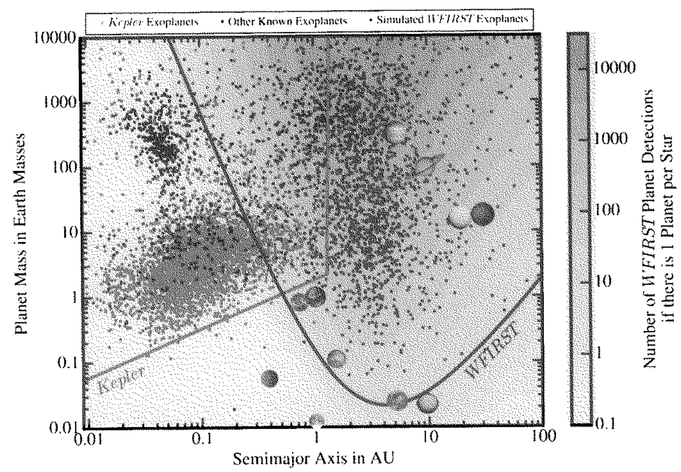
In cosmology, we have learned that our universe is both remarkably simple and remarkably strange. Nearly a century ago, Dr. Edwin Hubble's work at Mount Wilson observatory began our program of measuring the size and shape of our universe. Today, the Hubble Space Telescope and measurements of the microwave background continue this program. Over the past two decades we have learned that a simple model with only five parameters (the age of the universe, the density of atoms, the density of matter and the properties of the initial fluctuations), describes all of the basic properties of the observed universe. While successful, this model implies that atoms make up only 5% of the universe. Most of the universe is in the form of *dark matter* and *dark energy*.

Understanding the nature of dark energy is one of the most compelling problems in physics. Both Europe and China are leading missions to study dark energy. When I was in Beijing, I was impressed by China's plans to launch a large space telescope off of its new space station with a primary focus on studying dark energy. This telescope will have the world's largest space camera and use Chinese military technology to construct a large off-axis telescope. Fortunately, NASA is moving forward with the premier dark energy mission, WFIRST, the top ranked large space project in the 2010 astronomy decadal survey. It will measure the expansion rate of the universe and the growth of structure to unprecedented precision. WFIRST is meeting all of its technical requirements and is on track for a 2025 launch.

Astronomers have also learned that the solar system is far from unique. Using observations from the Kepler spacecraft and ground-based observatories, they have discovered thousands of exoplanets revealing a diversity of planetary architectures and a diversity of planetary properties. Shakespeare's line, "There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy" is perhaps our best guide as we contemplate whether there is life elsewhere in the Milky Way.

Just as the exploration of the cosmos has driven telescope design for the past century, the study of exoplanets and the search for life beyond our solar system will likely shape the telescopes of the coming century. NASA's TESS mission has begun revealing many new nearby transiting planets. When launched, the James Webb Space Telescope will be able to characterize the atmospheres of some of these planets. This is one of the powers of a flagship mission: JWST was not designed for transit spectroscopy but its enormous sensitivity in the infrared will enable it to make potential transformative measurements of planetary atmospheres. WFIRST's coronagraph is poised to be the next step in exoplanet characterization. The coronagraph should be more than 1000 times more sensitive than previous coronagraphs aboard Hubble and JWST. It will not only be able to image massive planets around nearby stars but will be the stepping stone for developing technologies for the next generation of great observatories.

Understanding planet formation requires use of a wide range of observational approaches. Within our own solar system, comets and asteroids are fossils of the early solar system. Radio and infrared observations reveal extrasolar planetary system in formation. With its microlensing observations, WFIRST will complete the census begun by Kepler and TESS. These should reveal thousands of planets in the outer regions of their solar systems.



This figure shows the discovery space for the Kepler and WFIRST mission as a plot of distance from the host star (measured in astronomical units (AU)) and planet mass. The Earth distance from the Sun is 1 AU. The plot also shows the planets of our own Solar system. The black points in the plot are the planets discovered by ground-based measurements of stellar radial velocities. Plot courtesy of M. Perry.

The astronomy community has just begun its next decadal survey. Led by Fiona Harrison and Robert Kennicutt, the survey is considering a range of possible projects including large optical telescopes likely launched in the 2030s that will be capable of characterizing extrasolar planets. Even these telescopes will likely be stepstones to even more sensitive telescopes that we will develop in the 2050s that will enable detailed characterization of planetary atmospheres.

Scientific advances in all of these fields are driven both by science pull and technology push. The desire to address major scientific questions pull technology development. Advances in technology pushed open the opportunity to study the universe in novel ways.

Historically, NASA has invested in technology development to enable its future missions. Over the past decade, the Space Technology Mission Directorate (STMD) has made these investments for both NASA's science and exploration programs. Regrettably, STMD is reducing these long-term investments for its future science missions and is focusing its resources towards the short term goal of returning humans to the Moon by 2024. I fear that this is eating

NASA's "seed corn" for future transformational science missions. I encourage the committee to consider directing the agency to make these long-term technology investments through instructing STMD to continue support SMD objectives.

NASA has long exploited technologies originally developed for our nation's defense, ranging from rockets to sensitive infrared detectors. In recent years, commercial advances are providing new technologies that should be repurposed by NASA for scientific discovery and exploration. The desire to build self-driving cars has led to substantial advances in autonomous systems. The machine learning revolution is not only improving facial recognition on Facebook and login-screens, but also providing novel tools for analyzing NASA's images of the changing Earth and of distant galaxies. The tools are also beginning to transform how we simulate complex physical systems. High performance computing hardware is shifting from CPUs to GPUs. These processors have not yet been used in space and are not being fully utilized in ground-based computation and analyses.

One of the challenges for NASA and for the scientific community is to be open to these innovations coming from new sources. Students will need to be trained not only in physics, chemistry and biology but also in data science and computer science. NASA's grant programs (and its referee process) will need to be open to entrants with non-traditional intellectual backgrounds. NASA will need to engage suppliers beyond its "usual suspects".

Perhaps, there is no area of technology that is changing faster than software engineering. NASA has been a leader in its open data policies and now has the opportunity to be a leader in open code policies. As the Academies' recent report on "Open Source Software Policy Options for NASA Earth and Space Science" notes, an open code policy can enhance and enable innovation and discovery, facilitate scientific reproducibility and encourage collaboration. Across both academia and industry, open software is transforming code development. While some of the scientific communities that work closely with NASA have adopted open software practices, others are fearful of their loss of control. The report recommends

> NASA Science Mission Directorate should explicitly recognize the scientific value of open source software and incentivize its development and support, with the goal that open source science software becomes routine scientific practice.

NASA's open data policy has been a model for other scientific agencies and for foreign space agencies. I hope that its software policies will also become a model through incentivizing openness.

I want to conclude by thanking the committee for the opportunity to discuss developments in NASA Science Mission Directorate. This is an exciting time for space science and a moment where our observations of Earth from space are vital for monitoring the health of our planet and determining appropriate policies. While NASA does face immediate challenges like successfully completing and launching JWST, this is an incredibly exciting time in space science. NASA satellites have enabled the discovery of 1000s of exoplanets, are detecting the optical counterparts of merging neutron stars whose gravitational waves have travelled for billions of light years to Earth, and are tracing the large scale distribution of dark matter and dark energy in the Universe. It has launched a satellite that will literally touch the Sun. NASA exploration of our solar system is revealing new insights into the origin of the solar system and perhaps even of life itself. Its satellite observations are deepening our understanding of the rapidly changing Earth. Most importantly, each of these discoveries raises new questions that future satellite missions will address in the years to come.

David Spergel is the director of the Center for Computational Astrophysics and the Charles Young Professor of Astronomy at Princeton University. He is the former chair of the Space Studies Board.

Using microwave background observations from the Wilkinson Microwave Anisotropy Probe (WMAP) and the Atacama Cosmology Telescope, Spergel has measured the age, shape and composition of the universe. These observations have played a significant role in establishing the standard model of cosmology. He is one of the leaders of the Simons Observatory, which will include a planned millimeter-wave telescope that will allow us to take the next step in studying the microwave sky and probing the history of the universe.

Spergel is currently co-chair of the Wide Field Infrared Survey Telescope (WFIRST) science team. WFIRST will study the nature of dark energy, complete the demographic survey of extrasolar planets, characterize the atmospheres of nearby planets and survey the universe with more than 100 times the field of view of the Hubble Space Telescope. Spergel has played a significant role in designing the coronagraph and in shaping the overall mission.

Since completing my Ph.D. work, Spergel has been interested in using laboratory experiments and astronomical observations to probe the nature of dark matter and look for new physics. Recently, Spergel has been active in the exploration of data from the Gaia satellite and observations made by Subaru's Hyper Suprime-Cam.

Spergel serves as co-chair of the Global Coordination of Ground and Space Astrophysics working group of the International Astronomical Union.

At Princeton, Spergel was department chair for a decade. During his tenure as chair, the department was consistently ranked No. 1 by both the National Research Council and *U.S. News and World Report*. He is an associate faculty member in both the department of physics and the department of mechanical and aerospace engineering at Princeton. He has been the primary mentor for over 31 graduate students, 35 postdoctoral fellows and 60 undergraduates, Chairwoman HORN. Thank you, Dr. Spergel. Dr. Sykes.

**TESTIMONY OF DR. MARK SYKES,
EXECUTIVE OFFICER AND DIRECTOR,
PLANETARY SCIENCE INSTITUTE**

Dr. SYKES. Chairwoman Horn, Ranking Member Babin, Members of the Committee, and Chairwoman Johnson, thank you for the opportunity to appear before you today.

As a former Chair of the NASA Small Bodies Assessment Group, I would like to begin by congratulating Dr. Zurbuchen on Administrator Bridenstine's recent announcement that NASA will be proceeding with the Near-Earth Object Camera mission, NEOCam. This space-based infrared survey of near-Earth asteroids and beyond has been a high priority for science, planetary defense, space resource utilization, and targets for human exploration for almost a decade.

This mission would not exist but for the vision, leadership, and shear management skills of the NEOCam P.I. (Principal Investigator), Dr. Amy Mainzer. Leveraging her experience as P.I. of the NEOWISE mission, Dr. Mainzer has spent 15 years building a team and a mission that promises remarkable discoveries, the retirement of the congressional mandate to find those objects that threaten our planet, and the necessary groundwork for expanding the future of our species in space. Dr. Mainzer is a role model not just for young women who aspire to have careers in science for young men as well.

I would like to—now to address the Administration's initiative to return to the Moon by 2020. In the President's proposed Fiscal Year 2020 budget amendment to NASA, the Administration asks for the authority, quote, "to transfer funds between appropriations accounts in the event that the Administrator determines that the transfers are necessary in support of establishment of a U.S. strategic presence on the Moon." The language authorizes transfers in this fiscal year and in subsequent fiscal years, including funds appropriated in prior acts. This is a disturbing request. It appears to allow for the complete reorganization of the agency, including expunging space science if desired, without any congressional oversight. This must be rejected.

On a more positive note, science provides essential support to human exploration. Scientists are the pathfinders literally. They define where we can go and what we can strive to do there. They determine the operational environment, the resources, and the hazards.

We should establish a dedicated science support team for human lunar operations. This should consist of lunar experts, as well as heliophysicists. Their purpose is not to do independent research but to marshal our rich data and knowledge of the Moon and its environment to support human operations, to anticipate their needs, to participate in planning, and to identify what new information is needed and how best and most cost-effectively to obtain it in a timely fashion.

I support the President's request to fund a lunar rover—at least one. It should be deployed in advance of our return to the Moon, particularly if there's desire to establish a long-term operational presence. The choice of a location at the South Pole is in part to access craters having permanently shadowed regions containing evidence for water ice. A rover is needed to assay any water ice and to inform us about what kind of resource recovery and processing would be required. In the meantime, we also need to study and mitigate the impact of human operations on the lunar environment, particularly its exospheric atmosphere.

Finally, every day, discoveries are being made not just by operating spacecraft but by work funded by NASA research and data analysis programs. These programs lay the foundation and justification for future missions. They provide a continuing return on investment on these missions by generating new knowledge even decades after the data was taken. These are core programs, and I'm concerned that they are not being supported at the levels recommended by the Planetary Decadal Survey.

I'm further concerned about the extent to which resources from these programs are being funneled to NASA center scientists without competition according to public statements, at times inconsistent, by NASA officials. The details of this program, including its costs and impact on resources for competed research programs need to be investigated and made public.

I believe that the American taxpayers deserve the most bang for the buck from their federally funded research programs. The core of that is competition. Scientists compete for grants and contracts all the time. It is not for the faint of heart. But competition is further undermined when NASA—I believe alone among other Federal agencies—hides cost information from proposal review panels and directs them not to take cost into consideration in their assessment of proposed research. This started before Dr. Zurbuchen's arrival. We need to look at the buck and not just the bang. And the subject-matter experts on review panels are in the best position to provide that assessment to selecting officials.

The United States has defined the forefront of solar system exploration for more than half a century, but we cannot take it for granted. Thank you.

[The prepared statement of Dr. Sykes follows:]

Statement of Mark V. Sykes
CEO and Director
Planetary Science Institute

Before the Subcommittee on Space
United States House of Representatives

June 11, 2019

Chairwoman Horn, Ranking Member Babin, and Members of the Committee, thank you for the opportunity to appear before you today. My name is Mark V. Sykes. I am CEO and Director of the non-profit corporation Planetary Science Institute, which celebrates 47 years of active participation in American solar system exploration. PSI supports more than 110 PhDs in 29 States, the District of Columbia, and a number of foreign locations. It is involved with almost every NASA solar system exploration mission. I have been a member of the planetary community for more than 35 years and have had the honor of serving as Chair of the Division for Planetary Sciences of the American Astronomical Society, chairing and serving on numerous NASA advisory groups and review panels, and serving as a founding Steering Committee member and subsequently Chair of the NASA Small Bodies Assessment Group. I am a Co-Investigator on the NASA Dawn mission to Vesta and Ceres, which formally ends with this month after 20 years since mission formulation. The views I express today are my own, and do not necessarily represent those of the Planetary Science Institute or any other organization or committee.

Summary of Comments to the Committee

The Committee has requested my testimony regarding the National Aeronautics and Space Administration's (NASA's) activities and plans for its Earth and space science programs, including the Earth Science, Planetary Science, Astrophysics, and Heliophysics divisions of the Science Mission Directorate (SMD), and associated issues. My key points to the Committee are (in no particular order):

Giving the Administration Authorization to Restructure NASA

- The Administration's proposed Fiscal Year budget amendment to give the Administration authority to restructure the agency as necessary in support of establishment of a US strategic presence on the Moon would pose, if implemented, a grave danger to the future of all American space science and our nation's space program in general.

Near-Earth Object Camera (NEOCam)

- The decision by the NASA Administrator to proceed with this mission is a substantial and important contribution to science, planetary defense, in situ resource utilization and finding future targets for human exploration.

- This is a singular accomplishment for the PI, Dr. Amy Mainzer, whose vision, leadership and management skills are responsible for creating a team and designing a mission that promises remarkable discoveries, the retirement of the Congressional mandate, and the necessary groundwork for expanding the future of our species into space.

- This mission builds on the successful NEOWISE mission, the PI of which is also Dr. Amy Mainzer. The deep heritage brought to NEOCam design and operations, maximizes its likelihood of success under the continuing leadership of Dr. Mainzer.

Returning Humans to the Moon by 2024

- Science provides essential support to the success of all human operations on the Moon, whether short or long-term.

- Science support should include rover reconnaissance and assaying of potential resources accessible to the South Pole station as soon as possible to lay the groundwork for sustainable surface operations beginning in 2028 or later.

- Planning for human operations should include telepresence and autonomous robotic operations for basic science, resource production experiments, facility fabrication, and other efforts.

- The plan under the Space Exploration Initiative for the development of astronomy on the Moon in concert with expanding human activity has been largely superseded over the past 30 years by the successful development of space-based observatories.

- Human operations on the Moon may significantly affect the lunar exosphere, increasing the need enhance its study in the near term while it is still relatively "pristine." The effects of human operations must be monitored and mitigation strategies developed in advance of return to the Moon.

Strengthening NASA's Planetary Research and Data Analysis Programs

- NASA should provide the data necessary to demonstrate that it has complied with the Planetary Decadal recommendation for R&A funding. This would be program element budgets at a minimum, with all assumptions and adjustments explained.

- Transparency is key. This includes program element budgets, directions and charges given to review panels, description of selection procedures (what information is conveyed from review panels to program officers, how are proposals ranked).

- Competition is essential to maximizing "bang for the buck."

- Maximizing return to the taxpaying public is undermined with hiding proposal costs from review panels and funneling research and data analysis funds uncompeted to NASA center scientists.

- Data analysis programs are no substitute for mission science teams

Giving the Administration Authorization to Restructure NASA

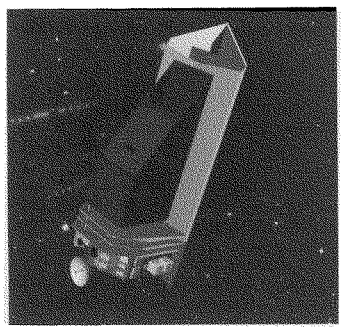
In the President's proposed Fiscal Year 2020 budget amendments, the Administration asks for the authority "to transfer funds between appropriations accounts in the event that the Administrator determines that the transfers are necessary in support of establishment of a U.S. strategic presence on the Moon. The language authorizes transfers in this fiscal year and in subsequent fiscal years, including for funds appropriated in prior Acts."

If implemented, this would pose a grave danger to the American space program altogether. It would allow for the restructuring of the agency. Space science could be radically reduced or expunged. All of this would occur without any Congressional oversight.

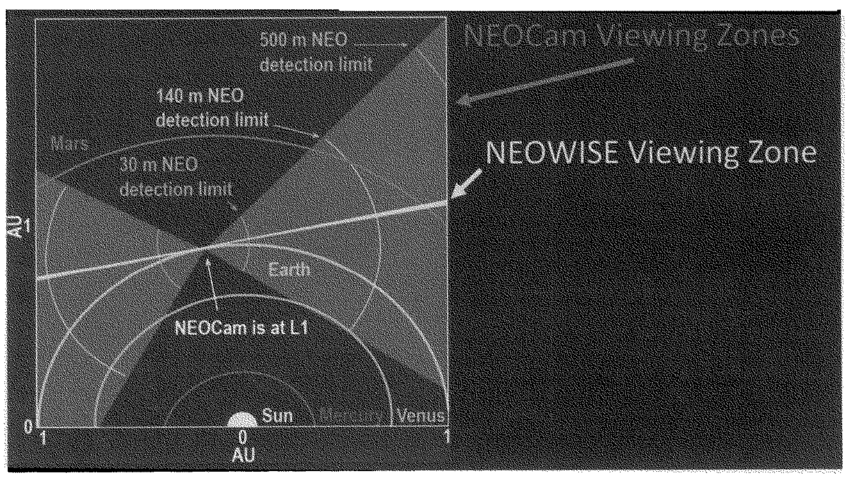
It does not matter who is the Administrator, the party in power, or the President today or tomorrow. This cannot be allowed under any circumstances.

Near-Earth Object Camera (NEOCam)

NEOCam was originally designed as an exploration mission to find, track, and characterize small bodies throughout the solar system. It was optimized for near-Earth object search and discovery, leveraging experience from the retasking of the Wide-field Infrared Survey Explorer (WISE) to search for near-Earth objects (NEOWISE). NEOCam is expected to discover ~100,000 new NEOs and millions of main belt asteroids.



It is a heavily reviewed project, first submitted to the Discovery program in 2005 and ranked Category II (recommended for acceptance, but at lower priority than Category I). It was submitted again in 2011 and received technology development funding which was applied to the development of new high-performance infrared detector material. It was submitted to the Discovery program in 2015 and awarded Phase A funding. Though not one of the two missions selected at the time for flight, it was given extended Phase A funding and refocused as a planetary defense mission.



One advantage of NEOCam over ground-based telescopes in searching for NEOs that could potentially hit the Earth is that it scans the sky interior to the orbit of the Earth as well as exterior. Ground-based telescopes only observe at night and so can only search for asteroids when they are outside the Earth's orbit. In five years it will detect 2/3 of "potentially hazardous objects" (PHAs) greater than 140m in diameter (the Chelyabinsk bolide was ~20m in diameter before it struck the Earth's atmosphere and ultimately exploded over Russia in 2013).

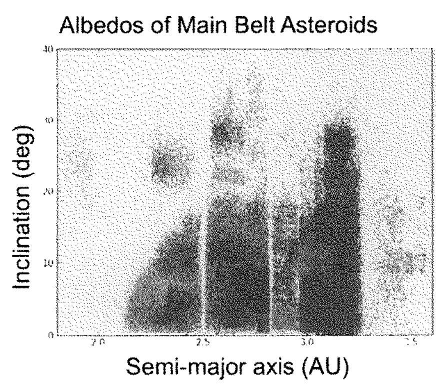
The strength of NEOCam lies in its use of thermal infrared light to search for asteroids. Asteroids are some of the brightest things in the sky at these wavelengths, greatly increasing the survey power of a modest size telescope. By looking at their emitted heat, instead of reflected light, NEOCam is able to detect the very dark objects missed by optical telescopes as well as measure the sizes for all objects detected.

As a planetary defense mission, the three goals of NEOCam will be to:

(1) identify impact hazards to the Earth posed by NEOs (both asteroids and comets) by performing a comprehensive survey of the NEO population;
(2) obtain detailed physical characterization data for individual objects that are likely to pose an impact hazard;
(3) characterize the entire population of potentially hazardous NEOs to inform potential mitigation strategies by assisting the determination of impact energies through accurate object size determination and physical properties.

NEOCam will determine asteroid sizes and albedos, which are important factors in determining the threat of a particular object. It will be able to identify sources of NEOs from the population of main belt objects and comets, which will provide insights into the likely physical properties of that fraction of the NEO population not detected by NEOCam.

A science definition team report commissioned by NASA and published in 2017 concluded that NEOCam was the most cost-effective means by which the Congressional mandate of finding asteroids hazardous to the Earth would be accomplished in combination with existing ground-based surveys.

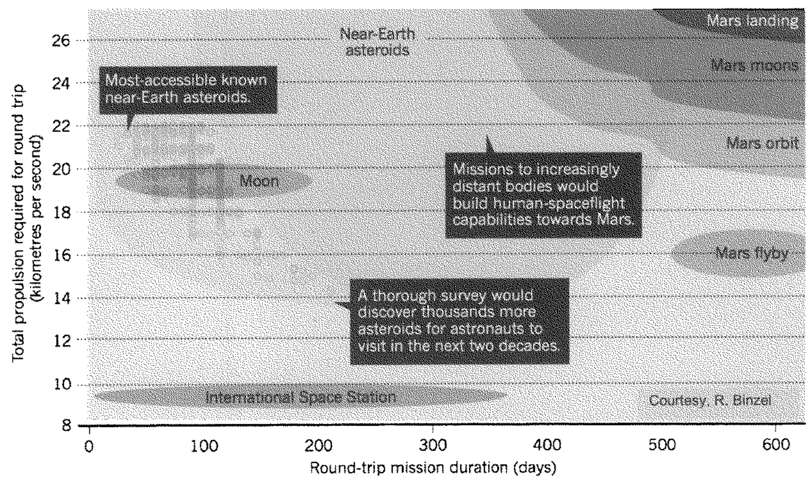


While no longer a science mission, NEOCam will still be providing a treasure trove of data that will more than double the known main belt asteroids and provide diameter and albedo information on more than 15 times the number of objects than currently.

NEOCam will provide new insights into the number, orbital distribution and physical properties of main belt objects, Jovian Trojans and comets. It will determine the origins of collisional families and NEOs. It will characterize currently rare populations of Earth Trojans and the population of asteroids interior to Earth's orbit. It will provide the most comprehensive collection of comet orbit distributions, sizes, and CO/CO_2 abundances.

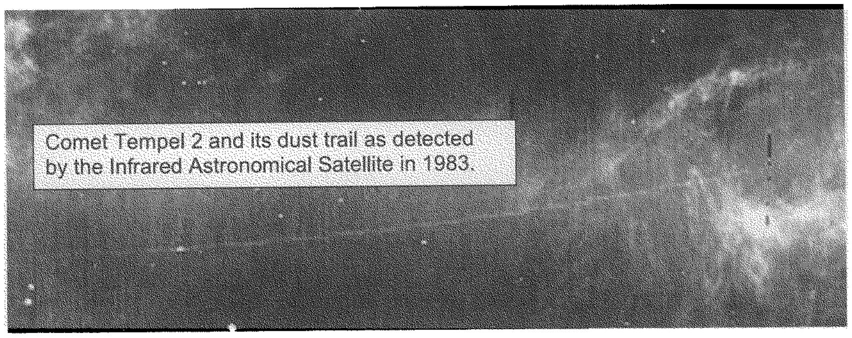
Another large benefit of the NEOCam mission is that among the large population of NEOs it will discover will be a subpopulation whose orbits are easier to get to than lunar orbit with very short round-trip mission times. This will enable:

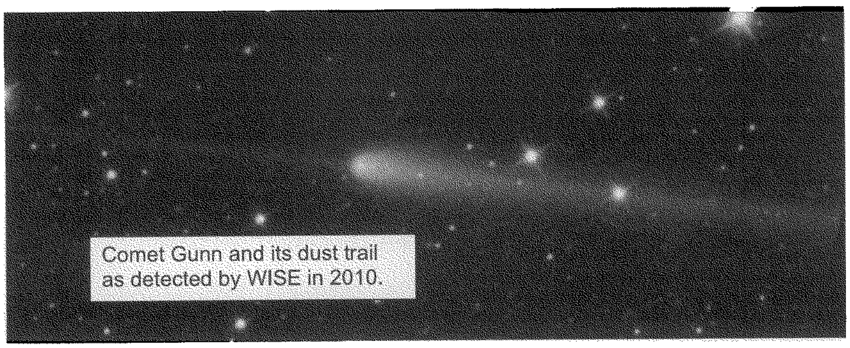
- Inexpensive, short-duration sample return missions, allowing for collection of materials that formed throughout the solar system (the origin locations of NEOs)
- Numerous dark targets (potential water source) for resource recovery demonstration experiments
- Numerous targets for human missions, requiring less energy that needed to achieve lunar orbit for a wide range of short to long stay times



One of my non-defense interests in NEOCam is that it will detect cometary dust trails. Cometary dust trails are fundamental to understanding the composition and origin of comets, the origin of the zodiacal dust cloud, the origin of meteor streams, and the hazardous environment for spacecraft approaching comets.

No mission provides as much value to as many diverse endeavors, from science to human exploration to planetary defense, as NEOCam. It's refinement over 15 years by its PI, Dr. Amy Mainzer, is a testimony not just to their dedication and diligence, but to the steadfast quality of work they have provided so that everyone may benefit from their efforts.



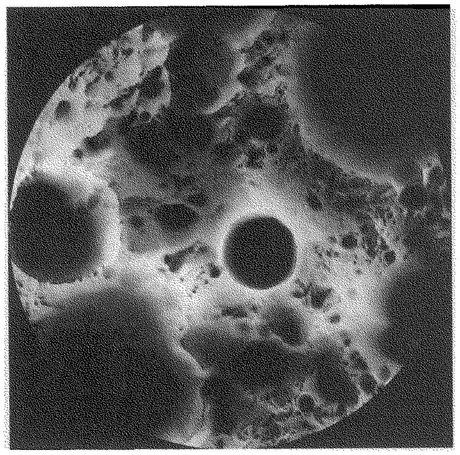


Returning Humans to the Moon by 2024

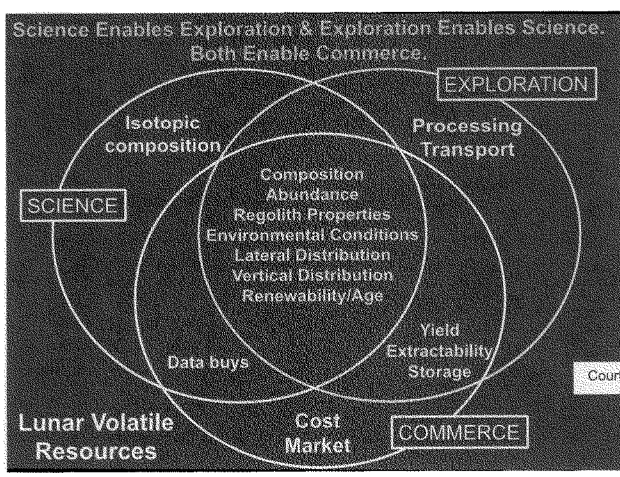
Science in Support of Human Exploration

Science will provide critical support to a human return to the Moon. This applies to lunar landing site determination and getting from one point to the other on the lunar surface.

The lunar polar regions are density imaged. By merging many images of the South Pole at different times, maps of illumination are created, revealing the shadowed regions of Shackleton crater near the center and other shadowed craters along with areas that receive more light. Images can also be used to construct terrain maps that include local slopes and indicate areas of surface roughness. This is also produced by laser altimeters. The existence of potential water ice in some of these shadowed regions are determined from neutron spectrometers on orbital assets, though at low spatial resolution. Water ice has been directly detected in such polar regions by spectroscopy of indirectly illuminated areas.



Volatiles are key to any long-term human operations on the Moon, including commercial activities if they arise. The volume of available water, how it will be extracted and processed for use on the lunar surface awaits future investigations in situ. So, an early rover or rovers will need to be deployed early on in the 2024 initiative, to lay the ground work necessary for the planned sustainable human presence, to commence in 2028.



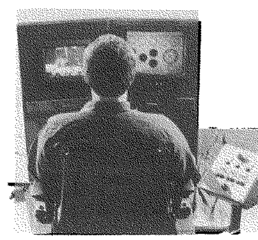
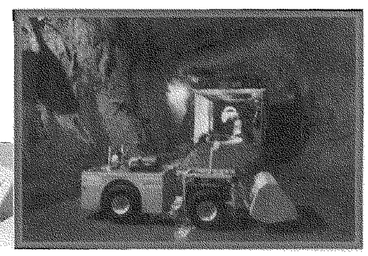
Courtesy, Clive Neal

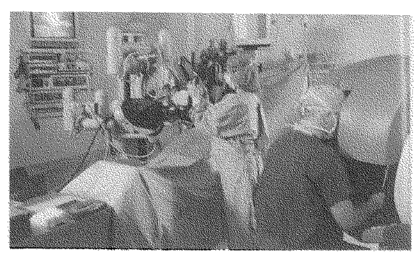
The Advantage of Telepresence and Autonomous Robotic Exploration

Space requires the extension of human presence in an unforgiving environment of vacuum and radiation. Fifty years ago, the logical choice was to shield human bodies within a spacesuit in order to operate outside spacecraft and on the surface of the Moon. Since then, technology has allowed us to extend our presence electronically to the point of being able to immerse ourselves in a remote environment and to interact with it as though we were physically present – telepresence. This should be a core capability that we take with us as we return to the Moon.

This require human proximity to minimize latency of action and reaction, and create that sense of 'being there' (a kinesthetic limit of ~0.4 seconds). The advantage of telepresence is that you can operate in a hostile environment, interacting with a surface at spatial scales not determined by the size of your gloves, at wavelengths and over wavelengths not limited by what you can see through a visor, with a precision that is not limited by the motor control of a human body.

On earth, this technology is manifested in everyday communications (cell phones and business conferencing), in surgery, in mines, and in nuclear reactors.



On the Moon, we will be overseeing resource mining and processing, loading and unloading supply vehicles, the construction of habitats out of lunar materials. We need telepresence to accomplish all this in a practical manner, which has the additional benefit of decreasing risk to astronauts. There will be some purposes for suited travel, but ultimately most will be through an immersive interface.

Autonomous robotic exploration is also required to explore the lunar resources to understand if they are viable for use to not only sustain humans on the lunar surface, but if they can be used to establish public-private partnerships with the commercial sector for long-term exploitation. Such a robotic campaign will potentially set the foundation for an expansion of the space economy.

Together, telepresence and autonomous robotic exploration will allow us to explore and operate in more challenging environments that was done during Apollo.

Astronomy from the Moon?

During the Space Exploration Initiative under President George H. W. Bush, in 1990, it was thought that astronomical observatories on the Moon offered the benefits of enormous scientific return and large community interaction. We envisioned the long-term goal of lunar based astronomy as the development of a diverse facility covering at all wavelengths of the electromagnetic spectrum.

Today, the dramatic improvement in capabilities for free-space observatories make the Moon a less compelling focus for investment in astronomical development.

One possible benefit to astronomy of having a human presence on the Moon, and hence in near-Moon space, would be to have the capability of maintaining large astronomical facilities at Earth-Sun L2.

Human Operations Impact on Science

During Apollo 12, the gas cloud surrounding an astronaut moving by was sufficient to saturate the Apollo 12 atmosphere experiment, indicating a rise in atmospheric density by at least two orders of magnitude. Gases can lurk for a long time as regolith night-time condensates to be released again at daytime temperatures. After Apollo 14 left, continuous monitoring showed that it requires years for local atmospheric pressure to return to normal.

Measurements of the lunar exosphere provide insights into the sources of hydrogen and water in the lunar soil and how water migrates to the shadowed polar regions. It also provides insights into the lunar interior and seismic activity. If evidence for a water source beneath the surface was found, that would have a large impact on the potential locations for human activity.

Substantial human operations at the South Pole, particularly once resource reclamation activities commence in earnest, could have a significant impact on the lunar exosphere. Perhaps dominate it, effectively ending its scientific study. This motivates several things:

- Prioritize lunar exosphere studies in the near term, before a return to the Moon
- Monitor the effect of human activity on the lunar environment

- Develop mitigation strategies to mitigate the contamination of the lunar environment, before a return to the Moon

Strengthening NASA's Planetary Research and Data Analysis Programs

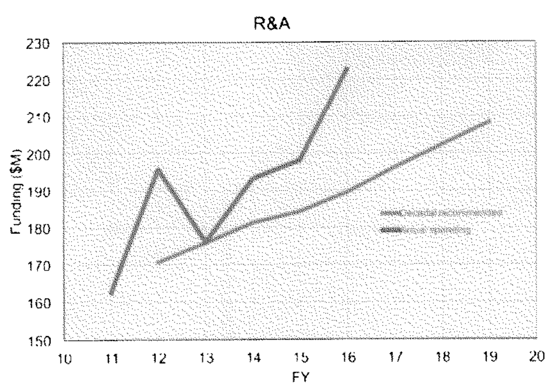
The importance of NASA's planetary research and data analysis programs was reflected in the following recommendation from the most recent planetary decadal survey:

"...**the committee recommends that NASA increase the research and analysis budget for planetary science by 5 percent above the total finally approved FY2011 expenditures in the first year of the coming decade, and increase the budget by 1.5 percent above the inflation level for each successive year of the decade." (p54)**

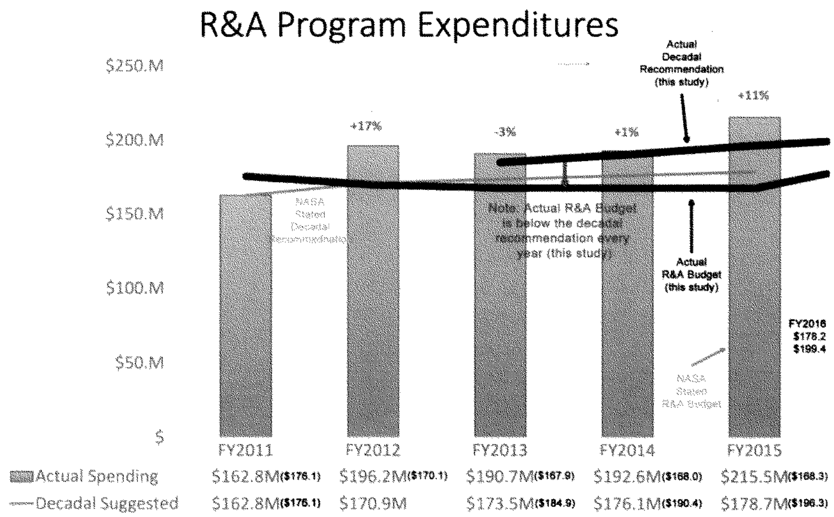
"It is also possible that the budget picture could be less favorable than the committee has assumed. **If cuts to the program are necessary, the first approach should be descoping or delaying Flagship missions. Changes to the New Frontiers or Discovery programs should be considered only if adjustments to Flagship missions cannot solve the problem. And high priority should be placed on preserving funding for research and analysis programs and for technology development.**" (bold in original text)

Did NASA Comply with the Planetary Decadal Recommendation for R&A Funding?

A review of the compliance with the decadal survey recommendations was conducted by the Space Studies Board, and released in the report, "Visions into Voyages for Planetary Science in the Decade 2013-2022: A Midterm Review (2018)." The conclusion was that NASA had significantly exceeded the decadal recommendation as shown in the chart below.



In sharp contrast to the detailed support provided to demonstrate that budget for technology programs had met the decadal recommendation, there is no granularity in the support for R&A above. This was actually the third attempt by NASA to demonstrate compliance with the R&A recommendation. The first effort submitted to the panel was challenged by myself. Using budget data provided by NASA, some through Freedom of Information Act requests, I determined that NASA had underfunded the research programs by more than $90M net (below). All the data I used and assumptions I made were published on http://planetarypolicy.org. I distribute this information to members of the Midterm Review committee and they requested additional information from NASA.



In the second attempt, NASA added various lines from the federal budget, some not reproduced correctly. I pointed out the errors to the committee and they requested yet more detail from NASA. The various efforts by NASA to provide budget numbers for research and analysis programs are summarized in the table below:

NASA PSD "R&A" FUNDING REPORTED ($M)

	2011	2012	2013	2014	2015	2016
MAY 2017	162.8	196.2	190.7	192.6	215.5	
NOV 2017	245	245	256	275	281	308
FINAL	162.5	195.7	176.1	193.2	198.1	222.6
SYKES	176.1	170.1	167.9	168.0	168.3	178.2

These are substantial variations, and in the absence of any supporting detail, at least at the program element level (as is provided for technology programs), none of NASA's numbers are reproduceable.

NASA has not been forthright in addressing the question of compliance with the Planetary Decadal recommendation for R&A funding.

Management Questions Regarding R&A Programs

The management of the planetary research and data analysis programs raises many questions. The "reorganization" of these programs in 2014, merging many disparate elements (e.g., Mars Fundamental Research, Outer Planets Research, Planetary Atmospheres) into one program (Solar System Workings) has been completely unwieldy. The review process has been questioned at public meetings (where a NASA official reported recently that the success rate of getting reviewers was 20%, suggesting few proposals are being reviewed by subject matter experts). Requests for public disclosure of directions given to reviewers and details of the selection process have gone unanswered. Budget information for individual program elements, which for a time was distributed at these meetings, but is now no longer distributed.

In "R&A Lunches" at the last two Lunar and Planetary Science Conferences, NASA officials raised concerns in the planetary community by reporting (in conflicting ways) that research funds were being funneled, uncompeted, to NASA center scientists. The details of this program including its costs and impact on resources for competed research programs need to be investigated in detail and made public.

Competition is Key and is Being Undermined

Every day discoveries are being made not just by spacecraft, but by work funded by NASA research and data analysis programs. These programs lay the foundation and justifications for future missions and realize the ongoing benefit in knowledge gained from our missions sometimes decades after the data was taken.

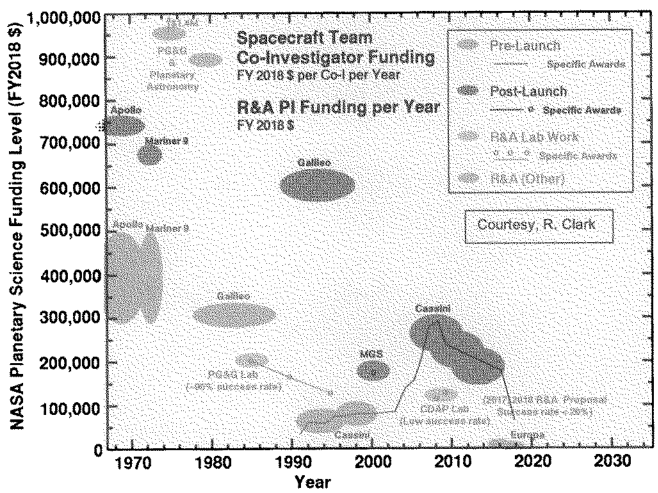
I believe that at the core of the success of these programs is competition. Scientists compete for grants and contracts. They compete for missions (setting aside the directed large flagship missions). It is not for the faint of heart. I would argue that through this competition, the people of this country get the most "bang for their buck."

This is undermined when NASA (I believe alone among federal agencies) hides cost information from proposal review panels, and directs them not to take cost into consideration in their assessments. For the great part of my career, proposal cost (and even details) were known and factored into the assessment of a proposal. This information is important particularly when expensive proposals may not allow the funding of several lower ranked proposals – only the subject matter experts of a review panel could provide good input on the relative scientific value of several proposals in the aggregate to one expensive proposal (I was on a panel once in which our top ranked proposal was requesting all of the funds available for new awards that year and we provided such an analysis to the program officer who used it to manage the situation successfully). Likewise, it is the review panel that is best positioned to determine whether the exceptionally low cost of a lower-ranked proposal would make it impactful.

Hiding cost reduces science return on the public investment in our research.

Data Analysis Programs are Burdened When Mission Science Teams are Underfunded

NASA missions are more complex, trying to answer more complex problems, but science teams are shrinking, as are their funding levels (see below). This pushes more mission scientists to seek more of their support from research and analysis programs, and raises the question of mission preparedness on the science side. This issue needs further study.



Mark V. Sykes – Biography

Mark V. Sykes is Chief Executive Officer and Director of the Planetary Science Institute at its headquarters in Tucson, Arizona. In 1978, he received his Bachelors in Physics from the University of Oregon where he studied the first known black hole system, Cygnus X-1. He subsequently studied Fourier optics and laser physics at the Oregon Graduate Center from which he received a Master of Electronic Science in 1982. He received his PhD in planetary sciences from the University of Arizona in 1986, and was awarded its Gerard P. Kuiper Memorial Award for his research. He discovered cometary dust trails and numerous rings of dust surrounding the inner solar system arising from recent asteroid collisions. He is a Co-Investigator on the NASA Dawn mission to Vesta and the dwarf planet Ceres. He has served as Chair of the Division for Planetary Sciences of the American Astronomical Society. In 1991 he was honored by the International Astronomical Union with the designation of Minor Planet 4438 Sykes for his discoveries, and in 2007 was the first recipient of the NASA Planetary Science Division Distinguished Service Award. In 2016, he received the AAS DPS Harold Masursky Award for Meritorious Service to Planetary Science.

Chairwoman HORN. Thank you, Dr. Sykes, and thank you to all of our witnesses.

We will now begin the first round of questions, and the Chair recognizes herself for 5 minutes.

Doctors Spergel, Gentemann, and Sykes, the Subcommittee will be working to reauthorize NASA in the coming months. What are your top three priorities for NASA reauthorization and why?

Dr. GENTEMANN. I'll start. As I said in my statement, it's to complete the Program of Record, to fund the designated observables, essential observations, and the Earth System Explorer high-priority observations.

Completing—following the decadal survey and why is because following the decadal survey recommendations is based on a huge community effort to maximize the societal benefit from Earth science observations, and this is the program that has been recommended to do so. Thank you.

Chairwoman HORN. Thank you. Dr. Spergel?

Dr. SPERGEL. My first—top priority would be to implement the priorities of the decadal surveys in Earth science, heliophysics, planetary science, and astrophysics. Another priority would be to assure that the STMD continues to make investments in science and developing technology for science.

Chairwoman HORN. Thank you. Dr. Sykes?

Dr. SYKES. Similarly, I think that we need to pay attention to the decadal recommendations of the—of having a balanced portfolio. Too much is often—attention is placed to the most expensive flagship missions which have the most cost volatility, and then we tend to lose the Discovery missions, the New Frontiers, the competed missions, which are cost-capped.

So there's a recommended cadence for these smaller missions. I think that needs to have more attention paid to it, and likewise, the smallest programs, the research and data analysis programs, need to be adequately—perhaps better than adequately funded because this is the foundation of our U.S. solar system exploration program.

Chairwoman HORN. Thank you. Dr. Zurbuchen, Administrator Bridenstine has stated publicly that he doesn't intend to redirect funds from other programs such as science to pay for the Moon initiative. However, as noted by Chairwoman Johnson, the Administration's budget amendment that was sent to Congress would, and I quote—and Dr. Sykes expressed concern about this as well—"authorize the National Aeronautics and Space Administrator to transfer funds between appropriations accounts in the event that the Administrator determines the transfers are necessary in support of establishment of the U.S. strategic presence on the Moon."

In addition to a recent article in *Ars Technica*, it quotes a NASA official as stating, "I don't think we're going to be able to get the entire budget as new money. We're going to have to look for some efficiencies and make some cuts internal to the agency, and that's where it's going to be hard."

Dr. Zurbuchen, are you currently planning or engaged in planning for scenarios for current or future cuts, delays, or deferrals or reductions in scope to Science Mission Directorate programs or missions for FY 2021 and beyond to fund the Moon-Mars 2024 program?

Dr. ZURBUCHEN. Our budget process for FY 2021 has just started, and I have not been directly engaged in any scenario planning with a massive downside to the science program.

Chairwoman HORN. OK. Thank you. If you were to have to look at those cuts, what would the potential for those cuts mean for the science programs and the balance within the science programs?

Dr. ZURBUCHEN. The way I have implemented every cut, also every upper, relative to a budget that I had before, is that I, and our team—and the Administrator has been very supportive in public as well as, you know, in our own meetings—we use the decadals to accommodate both uppers and cuts relative to that. That will mean, for example, that we actually protect the R&A programs with the highest priority, for example, in planetary, as in heliophysics. It would mean that we protect P.I.-class missions kind of over others and so forth.

That of course always comes with an asterisk. For example, when you have a launch window of a mission next year, it is unreasonable through the eyes of a taxpayer to take money out of that mission. It's much better to launch it instead of spending a half-a-billion dollars after the fact because of the fact that you moved some money out, $50 million or something. So it's with that caveat that we're using the decadal guidance.

Chairwoman HORN. Thank you, Dr. Zurbuchen. I have more, but I'll save it for the next round. I see my time is up. Ranking Member.

Mr. BABIN. Thank you, Madam Chair.

Dr. Zurbuchen, NASA recently awarded contracts to three companies as part of the commercial lunar payload services that will deliver landers to the Moon's surface. A condition of the procurement stipulates that awardees must be U.S. companies. One of the companies that won a contract features a design team from India that competed in the Google Lunar XPRIZE. A recent article by *Quartz* was titled, "America's First Private Moon Lander Will Be Engineered in India."

While this partnership appears to comply with NASA solicitation, the optics obviously are not good. Can you assure the U.S. taxpayer that we aren't simply outsourcing space exploration when we have companies designing lunar landers right here in America?

Dr. ZURBUCHEN. Thank you for that question. Of course, you recognize that there's three selections we made, including two where such questions did not come up. The one that you're talking about, this particular company, before we spend any dollars on it, has to undergo a full review of the very question you're asking. We already told them; we actually reviewed it at the beginning and we want to use the very same rules that we're using for launch vehicles as well that basically stipulate that the majority of all of the manufacturing and design of this particular lander has to be done in the U.S. We're going to go through one more review, an in-depth review to ensure that very fact.

Mr. BABIN. OK. Thank you. And, Dr. Sykes, we often hear that NASA should have a balanced science portfolio. However, other agencies like NOAA fund Earth-science activities. The NSF (National Science Foundation) funds astronomy, and NOAA and the Department of Defense fund heliophysics. How important is NASA funding to the planetary science community, and are there other significant sources of funding for planetary science other than NASA?

Dr. SYKES. Mr. Ranking Member, yes, that's a very important question. The planetary science community kind of stands out from these other communities because planetary science in the modern age is the creation of NASA. Astronomy was around for hundreds of years and is deeply embedded in universities. Heliophysics has communication concerns about space weather. There's industry and large industries associated with the important areas of Earth science.

Planetary really has NASA as its sole customer, and so NASA funding for our space exploration enterprise is basically the only market in town, and so the stability of that funding and—is critical for maintaining our ability to engage in that activity into the future.

Mr. BABIN. OK. And then, Dr. Zurbuchen, one more time, I represent Johnson Space Center, home of the Astromaterials Acquisition and Curation Office that documents, preserves, and prepares samples from the Moon, asteroids, comets, solar wind, and Mars. Is this office prepared to receive new lunar samples from future missions, or would additional resources be necessary to fully study these very important artifacts?

Dr. ZURBUCHEN. We are currently actually kicking off an analysis of that very question. See, there are samples that will come back with two characteristics we have not had before. Our first type of sample, especially from the southern areas of the Moon or the polar areas of the Moon I should say, because the north also has them——

Mr. BABIN. Right.

Dr. ZURBUCHEN [continuing]. Are cold samples, so cryo-type of samples that we want to bring back and hold there. Those are samples the likes of which we have not had before. The second type of sample that we're thinking about is coming back from areas where we want to analyze biology potential or at least the transition of chemistry to biology. In both cases we believe there's additional investments required, and we want to work with the Center to that. I already informed the Senate Director that that will occur.

Mr. BABIN. OK. And last, Dr. Sykes again, NASA plans on leveraging public-private partnerships to explore the Moon. They've also stated that they will take a more commercial approach. What customer other than NASA do you see on the horizon that would make this commercial?

Dr. SYKES. Well, everything's commercial at the end, Congressman. I think that's this is a new path for developing new vendors for the government. We've had the innovations by SpaceX and other companies that have developed rockets outside of the normal process and given us some great products that we could purchase. But at the moment the only customer that I see—and I can be wrong—for what's being done right now under the, quote, commercial thing is with the government as the primary customer.

Mr. BABIN. OK. Thank you, and I yield back.

Chairwoman HORN. Thank you, Ranking Member Babin.

The Chair recognizes Chairwoman Johnson for 5 minutes.

Chairwoman JOHNSON. Thank you very much.

Dr. Spergel, in your written statement, you noted the impressive work of other nations in pursuing missions to study dark energy, one of the highest priority questions about the nature of the universe. Could you elaborate on your comment? And do you have any concerns regarding the state of the U.S. astrophysics or science in general as compared to other nations?

Dr. SPERGEL. Well, there are two important missions. One is the European Space Agency's Euclid mission. Now, this falls in the category of something we've done a lot of, which is working together with the Europeans. We're a partner in the Euclid mission and are providing key components, and American scientists will participate in the Euclid work. And we've been designing the WFIRST mission to be complementary to the Euclid mission to carry out a science program that goes beyond Euclid and also complements it.

Perhaps of more concern is the Chinese space program. The Chinese are building a 2-meter optical telescope that will fly on their space station and are flying a large camera with that. Like us with WFIRST, they are taking advantage of technologies developed by their defense industries. And in one hand I think it's very good to see the Chinese starting to play a role in fundamental science. On the other hand, I think it's concerning that we might end up yielding leadership in an area where—you know, dark energy is something that was discovered by American scientists, and a lot of important work is being done here—to China.

And I see the Chinese universities trying to attract really outstanding people from the United States. I see them making big investments, and I think it's important that we maintain our leadership in science and technology, and I think that's why—one of the reasons why it's important that we continue to invest and push forward with projects like the WFIRST mission.

Chairwoman JOHNSON. Thank you. Any other comments from the other panelists?

Dr. SYKES. Congresswoman, I think that one thing we also need to keep in mind is that, yes, China is coming up, and they're becoming involved in all areas of space exploration. Their Chang'e missions have been very impressive, and what they're planning for the future will also be. But we need to be a leader not because we want to stay ahead of the other guy and let the other guy define the directions that we go in just to keep ahead, but we do it because it's good for our self, it's good for our economy, it's good for our society to continue to invest in these broad range across Earth science and astrophysics and heliophysics and planetary science to understand the world that we live in and to—you know, because as we pull back from that, you know, as evidenced by like trying to cut back on science team support for missions and things like that to—kind of nickel-and-diming things down, not that I'm advocating just throwing money at things, but to really be making solid investments in these areas, you know, that we will fall behind, and other nations will push ahead. You know, and they're not doing it to just get ahead of us. They're doing it for their own purposes, and we should be likewise deciding what our purposes are and pursuing them vigorously.

Chairwoman JOHNSON. Thank you. Yes?

Dr. GENTEMANN. I'd also like to add that in Earth science there's a similar situation which is the Chinese have a very robust Earth-observing satellite program, which is in contrast to our program where we're considering reducing the Program of Record and not following the decadal survey guidelines to do the essential and high-priority observations. China is launching Earth-observing satellite after Earth-observing satellite and working with Europe to establish leadership. And I would like—I hope that the U.S. continues our investment in Earth science so that we can remain a global leader in this area for—and it's for our societal benefit.

Chairwoman JOHNSON. Thank you.

Dr. SYKES. Congresswoman, if I can make one more comment, I don't see China as a threat. I see them as a potential partner in a lot of these areas, a partner for advancing what we want to do. And so I think it's a mistake to look at them as a bogeyman.

Chairwoman JOHNSON. Thank you. Yes?

Dr. ZURBUCHEN. I think the discussion that we're having here is a complicated discussion because both aspects are relevant. So, first of all, we are the leaders, and you should not have somebody else in my job if you would expect something other than me to say I worry about remaining the leader and I want to be ahead, actually moving forward faster than the ones who come behind us.

At the same time, I do believe one of the most important elements of science is the ability of nations to come together and work on problems that transcend boundaries or even political kind of boundaries that separate them from each other. Over a long time, it's those kind of activities that have brought us together as humans and have made us better overall. And I do hope, as we go forward and learn about these other countries, whatever it might be, whether it's China, whether it's Russia, whether it's other countries, that we get better at this because we sure want them to work on public science using the policy that we have pioneered where all data are out there for the entire science community to use worldwide.

Chairwoman JOHNSON. Thank you very much. My time is expired.

Chairwoman HORN. Thank you, Chairwoman. The Chair now recognizes Mr. Brooks for 5 minutes.

Mr. BROOKS. Dr. Zurbuchen, these questions and comments will be primarily for you. I'm looking at your written testimony to this Subcommittee, and it states, quote, "We are building for the long-term, and this time we're going to the Moon to stay," end quote. Later on, it says NASA, quote, "looks to land humans on the Moon within five years," end quote.

After describing the Artemis 1 and Artemis 2 missions, you go on to say, quote, "Then the Artemis 3 mission will send the first crew to the lunar surface using commercial human landing services that depart from the Gateway outpost orbiting the Moon," end quote.

So, at a minimum, we've got Artemis 1, Artemis 2, Artemis 3, the Gateway outpost that has to be designed, built, launched into lunar orbit. What's the total additional amount of money NASA needs in order to accomplish this landing on the Moon with humans by 2024?

Dr. ZURBUCHEN. That's a question that we're grappling with as we go forward and do the analysis. We already submitted for FY 2020, the incremental, you know, request at $1.6 billion for that year. The increments for 2021 and beyond will be part of the next budget proposal as we go forward. It's a question that we are currently working with, and of course my parts of that are the science parts, which are well-defined and I can talk about in much more detail.

Mr. BROOKS. Well, I'm on an authorization committee. Obviously, this is Space Subcommittee-related. And for us in Congress to be able to grapple with these things, we need some idea of how much cost is expected to be incurred over the next five years. Are you telling me that, yeah, we've got the $1.6 billion more or less for FY 2020 but we have no idea whatsoever what the next four years' cost will be in order to accomplish this human landing by 2024?

Dr. ZURBUCHEN. We're in the process of working through that right now and——

Mr. BROOKS. I understand you're in the process, but do you have any idea as to what the cost ranges may be, minimal to high, so far in this process, or do we literally have no idea what we're getting into when we talk about Artemis 1, Artemis 2, Artemis 3, and Gateway?

Dr. ZURBUCHEN. I—I'm not at this moment in time able to talk about all the elements of that, and especially in a directorate where most of the funding is incurred, which is not the Science Mission Directorate that I'm working on.

Mr. BROOKS Let me ask the same question but with respect to 2028, by which time we're supposed to have a sustainable Moon surface operation. Do you have any idea as to how much additional money NASA is going to need in order for us to have a permanent human presence on the south pole of the Moon by 2028, any idea?

Dr. ZURBUCHEN. The budget proposal that you have in front of you in 2020 had——

Mr. BROOKS. I'm talking not just that one year. I get the one year. But it's more than one year, and we've got to budget and plan. Do you have any range of numbers that you can share with us and the American people about what we're getting into when we try to put this outpost on the Moon?

Dr. ZURBUCHEN. At this moment in time I don't have a range of numbers that I can share.

Mr. BROOKS. All right. Let's talk about the Gateway outpost for a moment. Can you please describe what that is in a way that helps American taxpayers understand what they're paying for in terms of size or weight or rooms or how it might compare to the International Space Station, something that gives American taxpayers a reference point as to what this Gateway that's going to be circling the Moon on a permanent basis looks like?

Dr. ZURBUCHEN. The Gateway also is of course funded out of the Human Directorate, not out of our directorate but is—the way I think of it is like an outpost we have as a high-altitude camp next to a mountain. I'm from the mountains, you know. You go out there, it's a small, very simple——

Mr. BROOKS. OK.

Dr. ZURBUCHEN [continuing]. Place for——

Mr. BROOKS. What does small mean? When you say small, is that a one-room vehicle that's orbiting the Moon——

Dr. ZURBUCHEN. Perhaps it's a two-room vehicle or, you know, small relative to the size of number of people involved. It is simple at this moment in time to enable the early goal of 2024——

Mr. BROOKS. I understand the purpose of it. Let me go to my last question. With reference to the Gateway, you talk about solar electric propulsion. What is that?

Dr. ZURBUCHEN. Solar electric propulsion is a way of accelerating objects—spacecraft around. We use it in science. In this case it will be used for Gateway. It basically loads up—we bring a gas with us such as, you know, a noble gas or, you know, at that—cesium or something else that basically sits there, and we use an electric voltage that we get from—the power of which we get from the sun to accelerate those particles out the back and therefore propel us forward.

Mr. BROOKS. Well, thank you Dr. Zurbuchen, for your answer to my questions as best you're able. For what it's worth, no other representative of NASA has been able to tell us what this cost might be either.

Dr. ZURBUCHEN. Thanks.

Mr. BROOKS. Thank you, Madam Chairman.

Chairwoman HORN. Thank you, Mr. Brooks.

The Chair now recognizes Mr. Bera for 5 minutes.

Mr. BERA. Thank you, Madam Chairwoman.

So I understand Mr. Brooks' line of questioning is—you know, if we're thinking about multi-year and potentially multi-decadal missions, to have some sense of what that sequence looks like. When I think about it in the context of the Apollo mission, you know, I think there was a sense—a goal that didn't span one Administration but went from one Administration to the next and gave some certainty to NASA what that ultimate goal was.

I've heard each of you talk about the importance of the decadal survey of—kind of an objective process that is scientific, not politically based and then really kind of rank orders it. And each of you has emphasized the importance of once this survey is out there, to really try to, as best as possible, adhere to the recommendations in the survey because, again, when you're talking about science and you're talking about doing things that you may not have done before, there has to be a longer-term commitment.

Maybe, Dr. Gentemann, if you want to just describe, you know, briefly what the decadal survey process looks like and why it is so important.

Dr. GENTEMANN. Thank you. The decadal survey process starts with the Academies issuing one or two maybe RFIs, requests for information, from the community to one or both of those white papers. Often, you know, you have a specific word limit. Those white papers are generated—I think for the Earth science decadal there were 290. Some of these were written by one or two authors. Others were written by hundreds. So you end up having the opinion, a consensus opinion of multiple communities within the Earth science.

Those white papers are then given to subcommittees who distill them down. For the Earth science they were distilled to, I believe, 130 science questions that were seen as important by the community. Those 130 science questions were distilled to 35 observables. Those were then prioritized and ranked so that there could be—if one observable maybe addressed multiple scientific questions, you would prioritize that higher. This was a very difficult and thoughtful process, which is why the community stands behind it so strongly. Thank you.

Mr. BERA. And, Dr. Sykes, what's the downside of not trying to adhere to the decadal survey recommendations?

Dr. SYKES. Well, then it's just kind of random in terms of what happens. And our development becomes more constrained by political considerations than science considerations. So it's a way of coming together. The value of the decadal is it's supposed represent a consensus of the community. It's a process that could be improved. I know the Academy has its limits. If it was up to me—and I was involved in the first Planetary Decadal Survey—I would allow public comment on the committee reports and the steering committee report before things are finalized, but——

Mr. BERA. So it's not a perfect process, but it is——

Dr. SYKES. But it is——

Mr. BERA [continuing]. A very good process?

Dr. SYKES. Yes, it's a good process. We started to solicit white papers from the community back 20 years ago. The astronomers were very jealous of that because they would like to have the individual input. And getting that community input is, I think, essential.

Mr. BERA. And it's something that, you know—that we as Members of Congress with oversight should pay attention to and help guide us in our authorizing process, as well as kind of the appropriations process.

Dr. SYKES. If I could make one comment, Congressman, but often we're too distracted by the bright shiny objects. The largest projects recommended by the decadals, on the planetary side at least, it's the recommendation for the largest mission. It's not the top recommendation of the survey, and we need to pay attention to the little stuff, too.

Mr. BERA. Right. So in the decadal survey are they ranking order of what programs and objectives we should—they don't always rank order the big shiny objects first, though——

Dr. SYKES. Oh, yes.

Mr. BERA [continuing]. They do rank order.

Dr. SYKES. Yes. In planetary——

Mr. BERA. So——

Dr. SYKES [continuing]. They do. It's the recommendations for the largest missions, what kind of medium missions should be pursued——

Mr. BERA. So this is when we're authorizing and we're thinking about the budget, we should sit down with the NASA administrators, scientists, et cetera, and make some of those tradeoffs, taking small programs as well as large programs into account.

I'm about out of time, so I will actually yield back.

Chairwoman HORN. Thank you, Mr. Bera.

The Chair recognizes Mr. Olson for 5 minutes.

Mr. OLSON. I thank the Chair, and a big Texas welcome to our four expert witnesses.

I want to talk about going back to the Moon. I had the honor to spend a whole day with the most recent American to walk on the Moon, Captain Gene Cernan. He was back home in Texas 22 for a better part of a day to just drive around and talk to kids about getting excited about NASA and space. Our discussions were overshadowed by the Obama Administration's cancellation of the Constellation project, the one that was supposed to take us back to the Moon under George W. Bush. That was sort of shading the whole environment down there.

But Captain Cernan was very adamant about going to the Moon. He said that's the best place to go to prepare for going to Mars. He's pointed out that we've only spent 300 hours on the Moon, a little over a week, 12 Americans, not a whole lot of presence, six places we actually landed upon. We've missed a lot of the whole Moon. He also said we don't know what we don't know about the Moon. He pointed out, for example, that about 37 years after he walked on the Moon, we found out, hey, there's water on the Moon in those craters. And as you guys know, going to Mars or going in deep space, we have to have water for human beings to survive. So that's great progress.

My question is for you, Dr. Zurbuchen. You mentioned we can discover things on the Moon to help us go to Mars. As I mentioned, Captain Cernan agrees with you. Can you go further in detail on this topic? How can we help us learn more about the Moon that gets us to Mars quickly?

Dr. ZURBUCHEN. That's a really important question that you're asking, a question worth thinking about both from the science side but also from the human and technological side. There's a fundamental difference about being in low-Earth orbit and being away from Earth, and that has to do with the radiation environment that's out there. The radiation environment, of course, is much less in low-Earth orbit because of the fact that we have a magnetic field that kind of pulls away, directs away particles that are coming from deep space. That radiation environment, living in that environment for a longer duration is something that is existential to go to Mars but is something that we're going to learn being near the Moon on the surface of the Moon for a long time. We want to learn about resources like you talked about.

Ultimately, what we want to learn is actually to live off the land, if you want, relative to the resources that are there, whether it's the water there, some resources that may actually lead to companies or kind of commerce in other ways. That is a positive thing. It's something that we should think about, that has guided us. We would not sit in the United States here, this country we love, if the people ahead of us did not think that way. So it's about learning how to do that, also developing the technologies to sustain life in deep space.

Mr. OLSON. And as you mentioned, too, having access to water out of our orbit is huge because with our current propulsion systems it takes 10 pounds of propellant to put up 1 pound of water into orbit, so that means you have to have a huge rocket pulling all that water out of Earth going through our atmosphere. If it's there on the Moon, it's there for the taking, and I think that's something we should push. And getting there in five years is very, very doable if we make a commitment.

Another question for you, Doctor, is about the presence in this budget request for science. It's a decrease from the FY 2019 appropriations but still the highest ever proposed by an Administration. It's increased again. The President added an amendment there. He put on another $90 million. What does NASA plan on doing with that extra $90 million, and how does that differ from the existing commercial lunar payload services initiative?

Dr. ZURBUCHEN. I'm really glad for the question because it relates directly to what we just discussed. What we seek to do ahead of a human landing is actually bring robotic mobility, so a rover to the south areas, the polar areas of the Moon and actually look for water and the state it's in just in a way, as Dr. Sykes talked about in his testimony. That's what the additional $90 million allows us today, to buy that service to go over and accelerate going there ahead of humans going to that very region.

Mr. OLSON. I have a few more questions but not much time, so I'll yield back the balance of my time.

Chairwoman HORN. Thank you very much. The Chair recognizes Ms. Wexton for 5 minutes.

Ms. WEXTON. Thank you, Madam Chair, for yielding. And thank you to the witnesses for coming to testify today.

I am from Virginia where we have two incredible NASA facilities at Langley and Wallops Island. They both play important roles in many of NASA's scientific missions from launching CubeSats designed and built by Virginia students to testing key components of the Europa Clipper. So we know firsthand how NASA science missions increase our understanding of our solar system, deep space, and our own planet.

Dr. Gentemann, you wrote in your prepared testimony that the PACE and CLARREO Pathfinder missions proposed for cancellation in the Administration's FY 2020 budget request are considered part of the Program of Record for the decadal survey recommended—and recommended to be continued as a top priority. What would the impact be to our scientific understanding of the Earth and its changing climate if these two missions were canceled?

Dr. GENTEMANN. Thank you, Ms. Wexton. So the PACE mission is the Plankton, Aerosol, Cloud, ocean Ecosystem. It's a critical mission for quantifying the role of the ocean ecosystem and the global carbon cycle. When it's launched, it will give us unprecedented insight into the Earth's ocean and atmosphere, and collecting data on these systems is critical to understanding their effects on climate and Earth's habitability.

The instruments on PACE will allow for more detailed understanding of carbon uptake by the various phytoplankton species, and this is sort of the crux of it. This data will allow scientists and policymakers to be in a stronger position when prioritizing climate change mitigation strategies.

The CLARREO Pathfinder mission is designed to demonstrate in-space satellite intercalibration, and I've been involved in satellite calibration for over 20 years, and having this capability is just incredibly exciting to me as a scientist. It's essential to provide accurate well-characterized data. And it will provide the ability to intercalibrate instruments in space at accuracies 5 to 10 times beyond current capabilities.

These are both part of the assumed baseline Program of Record, and the Program—the decadal survey, all of these observations from these missions are interwoven into what sort of societal benefits we can expect by following this recommended guideline and including new missions so that it's all built on each other. Thank you.

Ms. WEXTON. Thank you very much. So I served in the State legislature in Virginia before I came to Congress, and one of the things that we have—it's kind of unique in Virginia is we have a 1-term Governor. And, as a result, we've got 4 years when one thing might be a priority for that Governor, and then another Governor comes in 4 years later and changes the priorities. So it had been cybersecurity, and now it's high-tech manufacturing or whatever it may be.

So seeing this decadal survey that is peer-reviewed and, you know, scientifically based is very encouraging to me rather than have, you know, the politics or the—you know, what a current administration may want to be focusing on be the focus.

But, Dr. Sykes, you testified that there were some shortcomings in the way that this program is administered and the issues with transparency and competition. Can you elaborate on that a little bit more?

Dr. SYKES. Well, yes, I believe competition is key, particularly in our research data analysis programs that we need to make sure where the money is going, to what parties, and so there's some open questions about that.

One of the main things which has come up over the last, you know, 6 years or so has been the hiding of costs of proposals from reviewers. I mean, this was something that, for the decades that I've been in the community and serving on panels and stuff, was a regular thing of being asked, well, is this good—is this a cost-effective proposal or, gee, this proposal is 3 times as much as 3 lower-ranked proposals. But what's the value of those 3 proposals taken together? That's not something a program officer can really answer.

I had an interesting—and I don't want to waste your time—experience where a proposer—top-ranked proposal wanted all the money of the program.

Ms. WEXTON. Imagine that.

Dr. SYKES. So we dealt with that. But—so making this information available, being transparent about costs, and also in terms of compliance with the decadal, just being open about what budgets are actually being spent. As you see in my testimony, there are some pretty interesting variations in terms of—in the planetary side what was considered research and analysis programs from 1 month to the next.

Ms. WEXTON. OK. Thank you very much, and I yield back.

Chairwoman HORN. Thank you, Ms. Wexton.

The Chair now recognizes Mr. Posey for 5 minutes.

Mr. POSEY. Thank you, Madam Chair. When you talk to people who aren't familiar with history and you mention the importance of our space program to the survival of our species, you get some chuckles and you even get some harassment. A lot of that diminished somewhat when we had that relatively small asteroid implode over Russia 1,000 miles from the nearest living person and injured 1,000 to 1,500 people. It did wake up some people to the possibilities.

The Planetary Science Division of the Space Mission Directorate is responsible for the Planetary Defense Coordination Office, which searches for, characterizes, catalogs near-Earth objects that could collide with the Earth. NASA established the Planetary Defense Coordination Office in 2016 in response to the NASA Inspector General's report. And the Trump Administration is calling for significant increase in near-Earth orbit funding.

Congress asked NASA to identify 90 percent of all hazardous near-Earth objects by 2020. NASA recently provided us a report that indicated they're not able to reach the goal in that time period but that the National Science Foundation's Large Synoptic Survey Telescope, coupled with a space-based infrared mission, could accelerate the survey.

Mr. Zurbuchen, I just wonder if you could tell me if NASA is now ready to go and what the time element may be.

Dr. ZURBUCHEN. Thanks for the question. We're committed of course that—to achieve that goal. We're not going to make it by 2020. I should have started a few years before. Sorry, but—no, I mean, look, I mean, we are—what we're focusing on are two things. First of all, we want to use any and all assets that are available, whether it's from the National Science Foundation or from our own missions to look at the data that are there and include it into the very database that you're talking about.

For example, the TESS mission that's out there in astrophysics is one of those sources that we're piping into that very analysis. The second one is through the increase by close to a factor of three of that particular budget line together with our team were enabled to actually do the very mission that you're talking about. In fact, we've started to invest in the technology, the sensor technology to detect those very cold objects. And it's our expectation to go forward with that mission in the next few years as a budget wedge becomes available in that line.

Mr. POSEY. OK. Mr. Sykes, did you want to comment on that? You had the largest grin when we were talking about survival of the species.

Dr. SYKES. Well, we do have the technology, and with the moving forward of the NEOCam mission, that provides the space-based infrared component. The limit to Earth-based observatories—and I'm a telescope jockey myself—is that you can only observe at night. And when you can only observe at night, that means that you can't see much interior to the Earth's orbit toward the sun. And we can be hit by stuff from there, too. The NEOCam mission is placed at Earth-sun L1 in between the sun and the Earth, closer to the Earth, and it's scanning tens of degrees closer to the sun, so it captures well inside the orbit of Venus, all the objects that are moving in there.

And there's an interesting thing—I'm sorry, please cut me off, but——

Mr. POSEY. Yes, go ahead.

Dr. SYKES [continuing]. That, you know, for instance, those Chelyabinsk-sized 20-meter type objects that exploded in the atmosphere over Russia. Well, about 5 times as many of those objects are hitting us—based on detecting flashes in the atmosphere and infrasound—than are predicted by the asteroid population models from ground-based observatories.

Why is that? Well, there is a possible answer is that you could have a breakup of interior—asteroid interior to the orbit of the Earth, and we're getting fragments from that. But you wouldn't pick that up in a ground-based telescope, but you would with NEOCam. So there's all kinds of—having this combination of these ground-based sources in combination with NEOCam is really going to put this to rest not by 2020 but, you know, probably within 5 years of its launch.

Mr. POSEY. The longest silence I've ever heard in this Committee is when the President's Chief Scientist, the NASA Administrator, and the Secretary of the Air Force were asked in one of our Committee hearings if a relatively small asteroid, the one that detonated over Russia, were headed for the Big Apple and we had a week's notice, which we wouldn't have, what would we do? And that's the longest silence we ever heard in this Committee.

Thank you. Thank you, witnesses.

Chairwoman HORN. Thank you, Mr. Posey.

The Chair now recognizes Mr. Perlmutter for 5 minutes.

Mr. PERLMUTTER. Thank you. And, Dr. Sykes, never apologize for your enthusiasm. We appreciate it. We've had some tremendous panels lately, and I just want to thank all of you for being here.

So I'm going to start with a couple softballs, and then we'll work it up from there. So, Dr. Zurbuchen, I understand you visited my alma mater last week——

Dr. ZURBUCHEN. That's right.

Mr. PERLMUTTER [continuing]. University of Colorado at Boulder, so I'm just curious what you were talking about, what kinds of science matters were generally discussed, and also how is NASA getting along with its university partners?

And then, Dr. Spergel, I'll let you kind of follow up from an academic institution point of view.

Dr. ZURBUCHEN. We at NASA think of the university partners as just that, they're partners. They're part of our mission without whom we cannot be successful. I therefore personally visit universities on a regular basis all around the country, and I was in Colorado talking about a variety of both missions that are ongoing there but also of ideas that are there that would make us better as we go forward.

The University of Colorado is among universities unique in the sense that it's the only university I'm aware of where during a Saturday football game, in the middle, the ad comes on and talks about NASA, so I love those games.

Mr. PERLMUTTER. Thank you. Dr. Spergel, how do you see the partnership or the relationship with NASA working between the institutions and the agency?

Dr. SPERGEL. Thank you. Generally working well in that I see it working in sort of two different forms, both of which I think are important. For the scientific missions, we often have situations where some of the leadership of the missions sit at the universities. For example, in the IMAP project that was just selected, my colleague Dr. McComas at Princeton is leading IMAPs and working together with NASA centers. When I worked on the Wilkinson Microwave Anisotropy Probe, we worked very closely with our Goddard colleagues.

And I think universities bring some flexibility, some innovation, perhaps most importantly really smart, eager, young students. And they bring a lot to projects.

And, on the other hand, I think what NASA centers do well is continuity. There are long-term capabilities that sit at the centers, and I think we can get a balance between the two.

To go—to echo something that Dr. Sykes talked about, another important role the university plays is in the research community. And it's the universities that train and develop graduate students. And one of the things that happens that we have to be very careful about when mission overruns, there's always a temptation to cut the research budget and research analysis budget in order to make sure that those projects go. When those things are cut, that eliminates, you know, graduate student careers——

Mr. PERLMUTTER. Right.

Dr. SYKES [continuing]. Because a lot of the funding goes to students. And I think educating the undergraduates and educating the graduate students is a really important role that the universities play in the whole scientific enterprise.

Mr. PERLMUTTER. A couple weeks ago we had a young woman who was a computer scientist who was the one who knit together all the pictures of the blackhole at the center of our galaxy. And she was, you know, brilliant and excited and enthusiastic, and she jazzed all of us up. So it's important to have that energy, that enthusiasm, and that, you know, new look at things.

So let's talk about space weather for a second. You know, we had a bill last cycle—it's coming back—to try to, you know, provide some more information about, you know, whatever kinds of flares, radiation, et cetera, are coming to us from the Sun. So can you talk a little bit, Dr. Zurbuchen, about, you know, what we're doing with the heliosphere and those kind of things?

Dr. ZURBUCHEN. The space environment of the Earth, just like the Earth itself, is a system that has both magnetic forces and plasma streams that interact with us as a technological society. The decadal of heliophysics that is driving our investments talks—has a key element, a whole chapter dedicated to space weather. That chapter 7 basically tells us we should, from NASA, provide and support to our operational agencies and, for example, look at L1 monitors as a continuing kind of capability. That's something we're working on right now with NOAA.

It also said that we should focus on research-to-operations work and also in reverse, look at how the operational data will help us drive more research. We started programs in both of those areas and are working with NOAA to do that. It also talked about investments in knitting together to create more strength and capability. It's something that we're working on and focused on.

Mr. PERLMUTTER. Thank you, and I yield back to the Chair.

Chairwoman HORN. Thank you, Mr. Perlmutter.

The Chair now recognizes Mr. Waltz for 5 minutes.

Mr. WALTZ. Thank you, Madam Chairwoman. And thank you so much, witnesses, for coming today.

So my questions today focus on the Commercial Lunar Payload Services, CLPS, the CLPS program, which is of course within NASA's Science Mission Directorate and provides commercial lunar landers for S&T payloads and has been described by NASA as the first major step to return astronauts to the Moon. So I'm a supporter of the program and in fact submitted an appropriations request to fully fund CLPS in FY 2020.

Bottom line, the 21st century space race is on. The Moon will be a critical part of it. On May 31, NASA awarded contracts to three companies under CLPS, and one of these companies, Beyond Orbit Inc., has elected to locate its lunar lander assembly facility in my district in Volusia County, Port Orange, Florida, which is fantastic, something we're very excited about. My district is just north of the Cape. And we're looking at at least 50 employees coming to our communities.

So my questions, and forgive me, Dr. Zurbuchen——

Dr. ZURBUCHEN. Yes.

Mr. WALTZ. So a condition, and I know there's been some questions on this already, but just to clarify, a condition of the CLPS procurement stipulates that the awardees have to be U.S. companies. So, again, can you assure Florida's taxpayers that NASA will not outsource its space exploration and will continue to focus on American companies, as it has throughout its history?

Dr. ZURBUCHEN. Absolutely. We will use the very same processes that we're using for launch capabilities in which we assure that the majority of all design manufacturing is right here for it to be falling under any contract that we would support from NASA. We actually have initiated a review of that, an audit of that right now before we put money into that particular company. We'll do so with others.

I, for now, actually think that it's a strength of the United States to attract companies that might have been invented elsewhere and come here and hire Americans and give them jobs and create economic activity right here on our soil.

Mr. WALTZ. No, I completely agree, and obviously there is an IP issue here, there's a national security issue, there's a number of issues wrapped around that on top of ensuring taxpayers receive that return on investment. So thank you for that.

You've also said, Dr. Z, and I agree with my colleagues, that the landers contracted through CLPS will, quote, "bring us closer to solving the many scientific mysteries of our Moon, our solar system, and beyond, and what we learn will not only change our view of the universe but also prepare our human missions to the Moon and eventually Mars." Can you elaborate on those thoughts and explain how these lunar payloads and the broader science mission is preparing NASA for human missions to the Moon and again, then, the follow-on to Mars?

Dr. ZURBUCHEN. If one looks at lunar science, what's really exciting about this is the Moon that we investigated during the Apollo program with the probes that we brought back, today is a very different science discipline than then. For example, even in the last few years, kind of a decade or so, again, the prevalence of water in—both on the inside of grains but also in—observed remotely from the Moon, it's basically reshaped our view of that—of our celestial companion.

So we have those kind of questions that actually were mentioned in the decadal in the planetary decadal that we can now do because we actually don't have to buy a whole billion-dollar spacecraft but we have a chance of doing through this new methodology. There's other questions that relate to the absolute age of the solar system, questions that are out there that actually have sharpened our understanding of activity, geologic activity in this planet that otherwise we did not think about before. It's those kind of questions we want to go up after, driven by principal investigators through a competitive process and taking advantage of that capability.

Mr. WALTZ. Well, you have a supporter here, presuming we need to spend those moneys smartly and efficiently.

I have Embry-Riddle Aeronautical University in my district. If you could submit for the record how the Mission Directorate partners with STEM institutions like Embry-Riddle for research and development, I'd be very appreciative. Thank you, and I yield.

Dr. ZURBUCHEN. Will do so.

Chairwoman HORN. Thank you, Mr. Waltz.

The Chair now recognizes Mr. Beyer for 5 minutes.

Mr. BEYER. Thank you. And, Chairwoman Horn, I really want to thank you for holding this hearing.

You know, we hear so much about the Administration's plans—constantly changing plans—to send humans to Moon or to Mars. It's actually great to hear about NASA's key science programs.

Dr. Spergel, in your testimony you stated that, quote, "Understanding the nature of dark energy is one of the most compelling problems in physics, and that Europe and China are leading the way on this." Without WFIRST, would we be behind other nations in studying dark energy?

Dr. SPERGEL. Yes, we would. I mean, now, we are partners with the Europeans on Euclid, but they are the leading—they're leading that study where we're partners there.

I mean, one of the—WFIRST, you know, is a mission that I think we want to do because of the compelling science it does.

Mr. BEYER. So tell me why—in layman's terms, why is dark energy compelling?

Dr. SPERGEL. It's 75 percent of the universe, and we don't know what it is, so it's most of what's out there. It's driving the expansion of the universe. It will determine the universe's fate, whether it expands forever, whether it's torn apart by a big rip, whether that—it turns around and collapses. It will be governed by the nature of dark energy.

Mr. BEYER. Will our research into dark energy also give us insight into dark matter?

Dr. SPERGEL. Perhaps. We—we're in the embarrassing situation of not knowing what makes up 95 percent of the universe. We know there's dark energy; we know there's dark matter. One of the things—actually working right now with an undergraduate with—my assignment for the train ride on the way back is to send him some detailed notes is, does dark energy interact with dark matter?

Dark matter clusters gravitationally. It behaves differently from the dark energy. It clusters in our galaxy so, you know, in this room we think there's lots of dark matter streaming through us. But, again, we don't know what it is.

There are a number of different ways that NASA missions are going after studying dark matter. The Compton Gamma Ray Observatory is looking for dark matter annihilation. We are mapping the large-scale distribution of the dark matter right now with Hubble. We will be able to do that with much more power with WFIRST. It can image more than 100 times the area in each image as the Hubble does.

Mr. BEYER. Let me jump on a WFIRST question because——

Dr. SPERGEL. Yes.

Mr. BEYER [continuing]. The President zeroed it out in his last couple budgets. We've put it back. You know, we like to say here it's the most important issue in the decadal survey that's been ignored by this Administration. But in casual conversations, you know, the cocktail-party conversations with NASA scientists, they say the other side of that is that by turning over $510 million or some billions of dollars to the outside government contractors, we're squeezing out the other essential science that needs to be done within NASA.

Dr. SPERGEL. Well, I think it's important that NASA maintain a balanced program, right? So you don't—we don't want to see WFIRST funded at the expense of severe cuts in the research program. This is why—and I think the—I would applaud the budget that's been—you know, come out of the Appropriations Committee here in the House this year that provide support in astrophysics both for research and analysis and for the WFIRST mission. And that goes beyond what was requested by the President's budget.

Mr. BEYER. Yes, thank you. Dr. Z, there's an article published 4 days ago in *Scientific American* that stated—and let me quote again—"The White House is considering whether to require scientists from NOAA, NASA, or other agencies to participate in the review, and the review being the program run through the National Security Council portrayed as a 'correction' to the National Climate Assessment according to sources involved in the planning." The article notes that Dr. Gavin Schmidt, a scientist at Goddard Institute for Space Studies was identified by the White House as a possible participant.

Are NASA scientists going to be required to debate the credibility of the National Climate Assessment? And how does NASA feel about its scientists being dragged into the climate skeptics at the White House?

Dr. ZURBUCHEN. And so, just like you, I've read the article in the press. I have personally not been engaged in any of the detailed discussions on that very issue. I would have to take additional information that you might want to know about this for the record.

Generally speaking, I believe that the science that we're doing, whether it's in this question or any other question, has the same kind of rules and that is it's perfectly fine to ask questions. We want to use the scientific method to answer those questions. And I have every belief that, no matter what the discussion is, that our scientists, whether at universities or within the government, would know how to handle this and other questions.

Mr. BEYER. Yes. And I certainly heartily agree that it's perfectly right to ask the questions, but you do have the concern when they say that being part of this could actually damage their careers, you know, by giving them the taint that they're part of something that is anti-scientific.

Dr. ZURBUCHEN. I just want to say that it will be a shame if the science community would turn on people who are asked to serve their government in whatever form to help in a discussion and do what scientists do. And if somebody said we can no longer talk to you, it would be a shame if the science community behaved that way.

Mr. BEYER. All right. Great. Thank you very much. Madam Chair, I yield back.

Chairwoman HORN. Thank you, Mr. Beyer. And thank you, witnesses.

The Ranking Member and I have a couple of additional questions, and then we will wrap this up. There were just a couple of things that we haven't quite touched on yet, and I want to say thank you to all of you. You've been very engaging and have been very helpful witnesses.

So, Dr. Spergel, I wanted to ask you about life and physical sciences. Right now, we know at—you're the former Chair of the Space Studies Board, and so you've looked across NASA's activities. And given that this science helps us understand how microgravity, how space environments impact human physiology and physical systems and then this research is helping inform our space exploration, that right now, this is under the Human Space Exploration Operations Mission Directorate, which is absolutely understandable.

What I'd like to hear is your views on how effective this placement of life and physical sciences is under the human exploration mission and in enabling our scientific progress and if you foresee any need for any potential changes moving forward in the placement.

Dr. SPERGEL. There's very good science going on in life and physical sciences. That said, I'm sometimes concerned that the Earth—the Exploration Directorate does not have the culture of scientific review that SMD has. I think one of the real strengths of the SMD is whether you're looking at big mission proposals or a small research grant, everything is evaluated by peer review and most everything is competed, and I think that's very important.

I think for physical and life sciences it's not—doesn't matter so much whether it sits in exploration or sits in SMD. I think the argument for sitting in SMD is it's doing science. The argument for sitting in exploration is that it informs particularly the life science aspects of the exploration mission. I think what is important is that it operate under the principles of competition and peer review.

Chairwoman HORN. Thank you very much. And I want to turn our attention now—several of you have addressed the issue of graduate students filling the pipeline and so, Dr. Z, the GAO (Government Accountability Office) and the NASA Inspector General have both identified challenges with workforce shortages related to our science missions. And clearly, that is an issue moving forward as we delve into this.

So I'd like to hear what are NASA's biggest challenges to sufficiently staff NASA science missions and your insight in the most efficient or effective ways to address those?

Dr. ZURBUCHEN. The IG report that you're referring to is specifically focused on Europa Clipper, and this has been with me for the year, so it was no surprise whatsoever. I'm focused on it. The issue there is that we're right now finishing off the Mars 2020 lander, and frankly, the top talent is working on that pushing it over the finish line.

I visited the group last week and actually had a review of that work yesterday. The good news is we're on track and we're making a lot of progress. The bad news is some of the people that we were going to put on the next mission were working, finishing off Mars 2020. That has to be the highest priority.

So we will take the recommendations, as provided by the IG, look at the schedule of what we're doing and going back. What I don't want to do is increase necessarily the Center size. What I want to do is think about how we distribute the work and how we in fact space strategic-scale missions relative to each other to make sure that we don't step on each other's feet.

The other thing that I've talked to the Director about is really focusing on mentorship of that next-generation leader that is out there. I strongly believe that the most important predictor for our leadership 10, 20 years from now is the talent that we're attracting and growing right now in our organizations. So I've focused on that as a second priority.

Chairwoman HORN. Thank you. Would any of the other witnesses like to comment on that last question?

Dr. SYKES. Well, I believe what Dr. Zurbuchen was referring to is operational personnel, but when it comes to the science team, that's another issue because the Mars scientists are not the people that are working on the Europa mission. And there seems to be some kind of consistent over the years scaling down of science team population and support and relying more on some of the research programs to try to pick up the slack for analyzing the data. And of course research programs can't do that in real time, which is what missions, you know, need. So that's another issue.

And as far as the young people are concerned, it's—I think we—it doesn't help young people to be pushed in the profession if there's no—you know, early career if there's no midcareer, so we need to be looking at that as well.

Chairwoman HORN. Thank you, Dr. Sykes.

Dr. Spergel, did you have——

Dr. SPERGEL. Yes, I just want to comment that I—one piece of this problem is the changing enforcement of our immigration laws, that we attract outstanding scientists from throughout the world to study here, and many of the best want to stay here. And I think it's important that we remain open to these outstanding scientists who want to remain here.

Chairwoman HORN. Thank you. Dr. Gentemann?

Dr. GENTEMANN. I'd also like to emphasize I think we're at a—the—attracting new talent, we're right at the cusp of this very exciting time in science where how science is being done is being reorganized. Within cloud computing and within open-source software, suddenly the types of questions that you can ask are completely different because you've sort of put aside a lot of the data wrangling and you can handle the information that you have very differently.

And being able to attract very exciting cutting-edge young scientists means that we also have to evolve as scientists in how we do science so that we can attract them and let them know that, you know, interdisciplinary science and open-source software will help them build their careers. And I think it's a very exciting time for science, and I think that we have a good chance of attracting these young technologically capable people. Thank you.

Chairwoman HORN. Thank you very much. Mr. Babin?

Mr. BABIN. Thank you, Madam Chair. I just have a couple of questions.

Dr. Zurbuchen, NASA is increasingly leveraging novel ways to acquire science data such as data buys, hosted payloads, ride shares, and CubeSats. Can you speak to the progress that NASA has made on this front?

Dr. ZURBUCHEN. I really appreciate that question. We look at commercial opportunities like that as opportunities to get more science per dollar. That's the motivator for us. Instead of building a whole spacecraft, we can take data that a commercial entity might acquire for other market needs and make——

Mr. BABIN. Right.

Dr. ZURBUCHEN [continuing]. That data available to the public. We have at this moment in time—besides the commercial lunar initiative we already talked about—a handful of other programs in play in which we're experimenting and learning about that, the most important of which in my opinion is the one focused on the data of our planet. We're in the middle of a year-long trial period. Frankly, what we're trying to learn is how to price in the market what we should pay for data. And that's a really important thing because on the one hand we want to spend—of course support our own U.S. companies. On the other hand, we also are deeply aware that we're spending taxpayers' money. So we're trying to figure out how to find that right price point. That's exactly what we're learning right now. There's other experiments just like it.

Mr. BABIN. OK. Well said. Also, the budget request proposes launching the Europa Clipper on a commercial launch vehicle despite appropriations laws that require the mission to be launched on an SLS (Space Launch System) to decrease the transit time and maximize the science conducted around Europa. How will the mission science be impacted by this particular decision?

Dr. ZURBUCHEN. If we launch on a commercial launch vehicle that could currently be available, it would add between 3 to 5 years or so of transit time depending on how we go there. That would have, of course, cost relative to the overall science team because we don't want to fire every scientist and then somehow hope we can hire them back.

Mr. BABIN. Right.

Dr. ZURBUCHEN. We need to keep essential teams there. It would of course require some resilience, and depending on where we fly by—for example, there's orbits where we would fly by Venus. Venus is a hot planet, so we have to do a different thermal design as we fly by there, so it's important to us to figure out which way we're going to go as we go forward. Of course, we will follow the law.

Mr. BABIN. You bet. You know what, I've got one more I want to ask if you don't mind.

Chairwoman HORN. Of course.

Mr. BABIN. Dr. Sykes, sometimes missions are delivered under cost. In order to incentivize cost-effective development of principle investigator-led missions, and this is to you as well, Dr. Zurbuchen, should NASA explore the possibility of allowing the principal investigator to use funding saved on development for research and analysis activities? If both of you gentlemen would like to answer that.

Dr. SYKES. Well, I think that in the context of the cost-capped missions that we don't want people to be busting the budget by borrowing from, you know, Peter to pay Paul here.

Mr. BABIN. Exactly.

Dr. SYKES. And I think that—and we don't do accounting across, you know, many years, you know, on these missions, so I don't know if that would be workable. So I——

Mr. BABIN. OK. Dr. Zurbuchen?

Dr. ZURBUCHEN. So, generally speaking, even though we have not made it a policy, what we have done to incentivize people under running their budget is by enhancing in some ways sometimes one-to-one their research programs. So many of the researchers frankly, what motivates them for a given mission, a P.I.-class mission, is that they want to do science, the mission is a path to the goal. The goal is to science. And so what we're trying to do is encourage them by basically not ripping away the money that they save the government and all of us but reinvesting that into a team because obviously we don't even have—we don't have just the good scientists. We already checked that. We also have a good leader, so we want to invest in those people.

Mr. BABIN. Well, thank you. Thank you very much. And with that, I yield back.

Chairwoman HORN. Thank you very much, Mr. Babin.

Before we bring this hearing to a close, I want to sincerely thank all four of you for being incredibly good witnesses. The—your insights, the clarity, the way you answered questions, and the reminder of the importance of the work that NASA Science Mission Directorate does and the importance of balancing the needs of science and being responsible stewards of our taxpayer dollars, as well as I think, Dr. Spergel, the reminder of the known unknowns and the unknown unknowns that are out there. So thank you all for being with our Committee today.

The record will remain open for 2 weeks for additional statements from Members and for any additional questions the Committee may ask of the witnesses.

The witnesses are excused, and the hearing is now adjourned.
[Whereupon, at 11:53 a.m., the Subcommittee was adjourned.]

Appendix I

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Thomas H. Zurbuchen
HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON SPACE AND AERONAUTICS

Discovery on the Frontiers of Space: Exploring NASA's Science Mission

Questions for the Record to:

Dr. Thomas Zurbuchen

Submitted by Chair Kendra Horn

Question 1:

You recently asked your division advisory committees to consider whether NASA is sufficiently able to support science that is multi-disciplinary, interdisciplinary, or high-risk-high-reward. What did they conclude from that effort, and what changes, if any, are you making as a result?

Answer 1:

NASA's Science Mission Directorate (SMD) recognizes the peer review process used to evaluate proposals is perceived to discourage high risk/high reward ideas and seeks to encourage more of these types of proposals. Internal data indicates that approximately 10% of proposals received by SMD are classified as high risk/high reward by peer reviewers, and that these proposals are selected at a higher rate than other proposals. Nevertheless, the perception that SMD is unwelcoming to highly innovative proposals is widespread. SMD is considering the best approach towards increasing the high risk/high reward proposals submitted to its solicitations, either through developing new solicitations or through modifying existing processes to allow proposers to indicate why they feel that their proposal is high risk/high reward and, in the event it is not selected for funding, subjecting the proposal to a further review for special funding.

SMD also recognizes that there is tremendous potential to make revolutionary scientific advances at the interfaces between disciplines and is considering ways to provide opportunities for integrated, interdisciplinary research that encourage collaboration. For example, the on-going collaboration between planetary science and astrophysics has enabled significant progress in the field of exoplanets and serves as a model for how other disciplines might work together in the future. We are expanding that work to include Heliophysics in order to understand the impact of different stellar types on their orbiting planets. Within the Earth Science Division, observations from the flight programs along with the research and analysis programs advance the interdisciplinary field of Earth system science, and the Applied Sciences program facilitates the use of Earth observations and applications among a wide variety of other scientists and stakeholders outside of the Earth Science Division.

Question 2:

Is JWST on track to meet the March 2021 launch date and $8.8 billion development cost cap?

Answer 2:

Yes.

Question 2a:

How much schedule reserve is still available?

Answer 2a:

The Program is performing within the re-planned budget guidelines, and carrying approximately 63 days of schedule margin to the March 2021 launch readiness with 7 days of liens.

Question 2b:

Has NASA conducted the review of the schedule and budget recommended by the GAO in their annual assessment of the mission in March of this year?

Answer 2b:

The GAO schedule and budget review recommendations were met following the Systems Integration Review in September 2019 and were formally part of the Key Decision Point D held in November 2019.

Question 2c:

What are the major milestones the JWST project still has to achieve between now and launch? What do you consider to be the greatest remaining risks?

Answer 2c:

As of January 2020, the remaining major milestones were: Observatory environmental testing (acoustics, sine vibe); final sunshield deploy, fold and stow. Although we have refined models, conducted numerous risk reduction activities, and have lots of experience and test data from the Spacecraft and OTIS element testing, the observatory-level environmental testing is still a first-time activity, and hence, carries some level of risk.

Question 3:

A common tenet reiterated in the decadal surveys is the importance of "balance," and you testified that "maintaining a balanced science program" is one of the "strategic focus areas" of the Science Mission Directorate. How does NASA evaluate whether or not a program or the programs within a division or directorate are balanced? What does "balance" mean, and why is it important? What are the signs a program is in or out of balance?

Answer 3:

NASA's Science Mission Directorate (SMD) strives to maintain a balanced portfolio that enables cutting-edge science from a diverse scientific community, explores new worlds, increases our understanding of the universe, and encourages STEM leadership both today and in the future. A balanced set of programs allows SMD to sustain progress towards our science goals and includes basic research, modeling programs, technology development, missions, mission data analysis, and data and information systems. We accomplish this through a range of mission types, from larger, less frequent, spacecraft missions to smaller missions that can be flown more frequently, many of which are led by principal investigators.

Smaller, less expensive missions generally have more permissive risk postures, and SMD has recently begun an initiative to better define the minimum oversight required for the least expensive missions that should allow proposers to take better advantage of the higher risk tolerance associated with these missions.

SMD relies on review by external advisory committees, both those in the NASA Advisory Council structure as well as the committees of the National Academies of Science, Engineering and Medicine, to ensure that its program is balanced across both subject areas and program types and sizes. Besides reviewing the potential science and technology opportunities of each program and project, these review bodies also evaluate cost and schedule performance, regardless of size and scope, in order to prevent a small number of projects from taking over the portfolio as a whole.

Question 4:

How is NASA balancing the scientific value of proposed Commercial Lunar Payload Services (CLPS) missions against the value for human lunar exploration?

Answer 4:

The CLPS project is led by the NASA Science Mission Directorate and is providing an innovative and cost-effective approach to performing science investigations of the lunar surface. The science investigations that are selected are aligned with the science objectives documented in the science Decadal surveys. Consideration is given to the alignment of the science objectives and the human exploration strategic knowledge gaps, many of which overlap. For example, both the lunar science community and the human exploration strategists and technologists want to find the horizontal and vertical distribution of volatiles on or below the lunar surface. NASA will continue to look for opportunities to fly payloads and conduct science investigations using the CLPS delivery services that align with science objectives and human exploration objectives, while also conducting pure science investigations on separate CLPS delivery missions to locations all across the lunar surface that are of scientific interest.

Question 4a:

Who has the final authority on which missions get approved, and what are the criteria for selection?

Answer 4a:

The NASA Science Mission Directorate selects the instruments and payloads that will fly on the procured CLPS delivery services. The delivery services are not NASA missions. They are delivery services provided by the CLPS commercial landing services providers. As part of the review process, representatives from the Human Exploration and Operations Mission Directorate and Space Technology Mission Directorate are members of the review panel along with scientists. The review panel provides recommendations to the selecting official after all of the proposals have undergone the standard review process. The criteria for selection is based on the standard Announcement of Opportunity (AO) and NASA Research Announcement (NRA) processes that SMD uses to evaluate all proposals.

Question 5 -5c:

What is the role of small satellites (SmallSats) and CubeSats in the Science Mission Directorate (SMD) portfolio?

a. Will SmallSats and CubeSats be one of many platforms that scientists might select in their science proposals?

b. What is NASA spending annually on SmallSats and CubeSats for science or technology demonstration purposes?
c. How will SMD SmallSat and CubeSat activities be managed, and how will the management align with the recommendations from the 2016 National Academies' report, *Achieving Science With CubeSats,* which included a recommendation that NASA "develop centralized management of the agency's CubeSat programs for science and science-enabling technology that is in coordination with all directorates involved in CubeSat missions and programs?"

Answer 5-5c:

The NASA Science Mission Directorate (SMD) has committed to investing about $100 million annually in small spacecraft capabilities, including CubeSats, due to their potential in enabling new science and the opportunity for small spacecraft technology to drive innovation toward mission success. The Directorate is building SmallSat partnerships across disciplines and sectors, and investing in early-stage research and technology through all of its disciplines. All SMD science areas are funding studies and flight missions using EELV Secondary Payload-Class SmallSats to CubeSats as platforms to enable innovative science measurements. Notable scientific and technology firsts have been achieved by NASA through these missions where results have been shared by the scientific community in the journal *Nature* and other leading publications.

Scientists are indeed incorporating SmallSats in their science proposals.

- In NASA's Earth Science Division (ESD), CubeSats are being selected as science payloads under Earth Venture Instrument competitive solicitations. For example, the Cyclone Global Navigation Satellite System (CYGNSS) is an eight-satellite SmallSat constellation that is currently on orbit studying the formation and intensification of tropical cyclones. In 2018, ESD selected the Polar Radiant Energy in the Far-InfraRed Experiment (PREFIRE), a two CubeSat mission.
- Also in 2018, NASA's Astrophysics Science Division (ASD) selected nine SmallSat study projects for advanced astronomical space-based measurements.
- In June 2019, NASA's Heliophysics Science Division (HSD) selected two SmallSat constellation missions: the Polarimeter to Unify the Corona and Heliosphere (PUNCH), and the Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites (TRACERS).
- Also in June 2019, NASA's Planetary Science Division (PSD) selected three finalist SmallSat missions under the Small Innovative Missions for Planetary Exploration (SIMPLEx) program.

The Agency's technology programs have increased investment in technology validation, through demonstration missions, in order to increase technology readiness and support risk reduction of future missions. This includes programs such as the In-Space Validation of Earth Science Technologies (InVEST) and the Heliophysics Technology Demonstration Mission of Opportunity (H-TIDeS). Additionally, a significant number of existing technology programs are now emphasizing investment in miniaturization of science instruments.

The Earth Science Division is also implementing a Small Satellite Constellation Data Buy pilot program to evaluate how data derived from privately operated small satellites could augment the Agency's Earth observations for the purpose of research and applications. NASA-funded researchers are currently examining data from three providers – Planet, DigitalGlobe, and Spire – to help determine their utility for advancing NASA's science and applications goals. The results of this assessment are expected in early

FY 2020, and will help inform how NASA leverages commercially available data to advance NASA science and applications activities.

With respect to the management strategy, as stated in our August 2017 response letter to the National Academies, NASA believes close coordination – rather than centralized management – is the more effective approach toward advancing its diverse goals. In setting up this coordination process, NASA has continued to focus on communication, coordination, and consistent guidance related to SmallSat/CubeSat activities and processes. NASA's Small Spacecraft Strategic Plan is at the center of our approach to guide coordinated activities among the mission directorates for high-priority science, support to human exploration, disruptive technology innovation, and access to space with SmallSats and CubeSats. This strategy is predicated on the worthiness of SmallSats and CubeSats in advancing the NASA 2018 Strategic Plan goals of Discover, Explore, Develop, and Enable, while accepting higher risk for greater potential scientific gain. SMD established a Small Satellite Working Group (SSWG) to coordinate activities across our four research divisions. The SSWG, in turn, has representation on the NASA-wide Small Satellite Coordination Group (SSCG), which coordinates activities with the Human Exploration and Operations Mission Directorate (HEOMD), including the CubeSat Launch Initiative (CSLI), as well as platform technology projects in the Space Technology Mission Directorate (STMD). Since SMD, HEOMD, and STMD fund SmallSats/CubeSats for different purposes, it would be inappropriate to centralize management as their selection and management needs to remain closely integrated with the organization with budgeting authority. However, NASA will continually re-assess its management approach as it advances its SmallSat/CubeSat investments.

Question 6:

In his testimony, Dr. Sykes stated that NASA is "hiding proposal costs from review panels" and "funneling Research and Analysis funds uncompeted to NASA center scientists." How does NASA respond to Dr. Sykes' statements?

Answer 6:

NASA SMD relies upon competition among research proposals to ensure the highest science value for taxpayer dollars. Peer reviewers are asked to examine the scientific merit, relevance, and cost reasonableness of proposals. "Cost reasonableness" is interpreted to refer to the balance between the work proposed and the various resources requested. To evaluate this balance, peer reviewers do not need to know participant salaries or benefits or organizational overhead. Focus instead is on science value, including the key question of whether the proposed scientific research can be accomplished with the stated resource levels. NASA's Science Mission Directorate has been redacting salaries, benefits and institutional overheads of all proposal personnel from the proposal copies seen by peer reviewers since the release of Research Opportunities in Earth and Space Science (ROSES) 2016 with no demonstrable reduction in the quality of the science supported.

Science Mission Directorate funding supports research at NASA Centers as well as at external organizations (*e.g.,* universities, non-academic non-profits). Unique among Federal Government science organizations, NASA's internal (civil servant) researchers have traditionally competed for the same funding as external researchers. In 2016, it was determined that because of this competitive-funding model, NASA expends significant resources competing for its own research funding. As a result, NASA civil servant scientists spend large amounts of time writing proposals to perform the research that, in many cases, NASA originally hired them to perform. Moreover, the triennial proposal cycle made it difficult for NASA to fund science-enabling activities and assets that require long-term management and specific expertise.

In response to this determination, NASA embarked on a multi-year pilot program, the Internal Scientist Funding Model (ISFM), to reduce the burden on NASA scientists and more efficiently support their research and science-enabling activities. Research funded through the ISFM process is expected to be strategic, forward-leaning, and distinctive — it should be work that is best led by or performed at a NASA Center and provides value to the broader scientific community. In the current implementation of the ISFM, external (non-NASA) peer review is used to improve planned research and to later evaluate progress of that research. One of the key tenets of the ISFM is that the balance between funding for internal and external researchers be unperturbed by the new approach to funding internal research. An assessment of this neutrality is one of the ten measures of success for the pilot program.

Question 7-7a:

What is the current status of the Ionospheric Connection Explorer (ICON) mission launch date?

a. Are the issues with the Pegasus launch vehicle ones we have seen before, or could have anticipated? What is being done to address the issues with the Pegasus launch vehicle?

Answer 7-7a:

This issue has not been seen on previous Pegasus launch vehicles, and this issue was not anticipated. It appears to have occurred as a result of a complicated set of interactions on the launch vehicle that were not observed on previous Pegasus vehicles. The Pegasus for ICON was modified to minimize the issue and then launched successfully on 10/10/19.

Question 7b:

Is a different launch vehicle an option?

Answer 7b:

A different launch vehicle would have delayed the launch date many more months, potentially more than a year. ICON launched successfully on 10/10/2019 aboard the Pegasus launch vehicle.

Question 8:

Our full Committee Chairwoman Johnson and Ranking Member Lucas sent a letter to the FCC urging a reexamination of the 24 GHz spectrum auction after concerns were raised by NASA and NOAA. How is NASA preparing for and mitigating against potential incursions into protected spectral windows for science?

Answer 8:

The spectrum management environment is dynamic and it continues to be shaped by technological advancements, evolving policy frameworks, and emerging operating requirements, posing both opportunities and challenges for NASA spectrum equities. NASA remains committed to proactively addressing these issues both to meet our own mission requirements and to contribute to policy decisions for the efficient use of this valuable, but limited resource. This includes participation in spectrum repurposing initiatives in response to national policy directives as well as Congressional legislation.

NASA remains engaged in efforts to study the impacts of the 24 GHz spectrum auction to in-band and adjacent-band existing and planned operations, particularly with respect to the compatibility between incumbent passive microwave sounders and future 5G systems. In our response letter to Chairwoman Johnson and Ranking Member Lucas, dated June 27, 2019, we provided additional details on these activities. Through active participation in the ongoing executive branch deliberations we can help protect vital national technological and economic interests enabled both through the advancement of 5G wireless communications and preeminence in weather forecasting.

Question 9:

How is the Science Mission Directorate developing the next generation of mission Principal Investigators (PIs)? What are the challenges and opportunities you see in the PI workforce pipeline?

Answer 9:

NASA's Science Mission Directorate (SMD) relies heavily on the innovation and excellence of the science community to develop new mission concepts that expand our capabilities and grow our portfolio. Based on past success and guidance from the National Academies of Science, Engineering, and Medicine, most NASA missions are initiated by proposals from teams led by PIs. Over the past several years, SMD has observed that the diversity of mission PIs does not reflect the diversity of the broader science community. In order to encourage an infusion of new ideas to ensure continued scientific excellence, SMD is working to provide opportunities that will expand the pool of future mission PIs with input provided by members of the scientific community, in particular observations and feedback from a PI diversity workshop held in Washington, DC in November 2018. More recently, SMD gave a NASA National Colloquium, hosted at the University of Colorado, on writing successful mission proposals in which we shared lessons learned about what makes a proposal successful, common mistakes, and experiences from the point-of-view of both proposers and the NASA selection official. The talk was attended in person by 200+ people and has been viewed online by 2000+ people.

The decision to become a mission principal investigator is often influenced by the experiences a researcher has at the graduate and postdoctoral level, decades before they may be ready to submit a proposal to NASA. There are also multiple pathways to mission leadership, through technical achievement and scientific leadership. Therefore, SMD has developed a long-term strategy to cultivate future PIs from the start of their careers through their first mission proposal. This strategy focuses on three areas: 1) increased awareness of what it means to be a PI and the requirements for that position, 2) inclusion as part of a mission team for early career researchers in order to gain hands-on experience, and 3) investigating the pathways that past PIs have taken in their careers prior to assuming this role.

Question 10-10a:

This past fall, the Science Mission Directorate (SMD) issued a Request for Information (RFI) for an SMD-wide strategic plan for scientific data and computing and held a workshop on the topic

a. Will NASA be releasing any findings or outputs from the RFI and the workshop?

Answer 10-10a:

A summary of the responses NASA received a part of the RFI on the Strategic Plan for Scientific Data and Computing is posted on the SMD public website (https://science.nasa.gov/researchers/science-data).

Question 10b:

When do you anticipate SMD will release a strategy on science data, and what will it cover?

Answer 10b:

In December 2019, NASA SMD released the Strategy for Data Management and Computing for Groundbreaking Science 2019-2024 (available online at https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/SDMWG%20Strategy_Final.pdf), the scope of which encompasses all SMD science data systems, including high-end computing. The strategy will promote more efficient and effective data management across the four science divisions, as well as enable cross-disciplinary discovery and analysis of science data.

Question 11-11a:

At the most recent NASA Advisory Council Science Committee meeting May 21-22, 2019, the Science Mission Directorate (SMD) sought feedback on a draft of a new strategic plan for SMD and a separate lunar science strategy.

a. When will the strategies be released?

Answer 11-11a:

The draft NASA Science Plan was released to the National Academies of Science, Engineering, and Medicine (NASEM) Space Studies Board (SSB) which convened an ad hoc committee, held a two-day meeting in August 2019 to review the plan, and provided feedback to NASA SMD in October 2019. NASA SMD is addressing the feedback now and plans to release the NASA Science Plan in March 2020. The Science Strategy of the Moon was completed in September 2019 and continues to be updated as Artemis continues to be developed. Both documents reflect the revisions contributed by the NAC Science Committee at their May 2019 meeting.

Question 11b:

What role will the strategies serve, and what is their relationship to the decadal survey?

Answer 11b:

Finding answers to profound science questions requires a focus on the scientific priorities identified by the National Academies of Science, Engineering, and Medicine (NASEM) through their decadal surveys and by supporting national priorities in science and exploration. The first strategy specified in the draft NASA Science Plan is therefore to execute a balanced science program based on discipline-specific guidance from the NASEM and the second strategy is to participate as a key partner and enabler in the agency's exploration initiative, focusing on scientific research of and from the Moon, lunar orbit, Mars, and beyond.

The draft NASA Science Plan for 2019-2024 delineates an ambitious program that builds on current activities and drives change in high-priority areas across the entire portfolio. The Science Plan should therefore be thought of as a vision to enable exploration and scientific discovery through innovation, interconnectivity and partnerships, and innovation. The decadal surveys provide discipline-specific guidance whereas the Science Plan speaks to strategies that will enable SMD to implement decadal survey recommendations and respond to national priorities through new and innovative technologies, cross-disciplinary science, and partnership models beyond traditional ways of developing missions.

The role of the draft Science Strategy of the Moon is to achieve decadal survey objectives over a plethora of disciplines, perform all research to NASA Science standards (i.e., competitive selections, open data policy), and enable human exploration, which in turn enables more science. The draft Strategy includes approaches to implement decadal science such as using Commercial Lunar Payload Services (CLPS) contracts to deliver precursor robotics (instruments on and near the Moon); crewed missions that will conduct investigations on the lunar surface (including sampling); and rover and lander capabilities. It also leverages other community documents such as the National Research Council's Scientific Context for the Exploration of the Moon (2007).

Question 11c:

How do decadal surveys and other community consensus documents inform the development of the strategies?

Answer 11c:

Through the decadal survey process, the scientific community provides input on key science drivers and the recommended balance between strategic-scale missions, competitively-selected small and mid-scale missions, technology programs, and research and analysis programs. This guidance is designed to enable lasting leadership by providing focus on the highest priority science questions the Nation should be addressing and highlighting areas of opportunity to grow the scientific community's capabilities. Each SMD division manages their portfolio in accordance with this guidance and progress against the decadal surveys is assessed by NASEM as part of their mid-term reviews.

By comparison, the draft NASA Science Plan for 2019-2024 delineates an ambitious program that builds on current activities and drives change in high-priority areas across the entire portfolio. The decadal surveys provide discipline-specific guidance whereas the Science Plan speaks to strategies that will enable SMD to implement decadal survey recommendations and respond to national priorities through new and innovative technologies, cross-disciplinary science, and partnership models beyond traditional ways of developing missions. As one example, the Science Plan seeks to advance discovery in emerging fields by identifying and exploiting interdisciplinary opportunities between traditional science disciplines. The on-going collaboration between planetary science and astrophysics has enabled significant progress in the field of exoplanets, and emerging opportunities exist to use the Earth as a laboratory in support of habitability and heliophysics scientific questions.

Regarding the draft Science Strategy of the Moon, the science goals therein were driven by community-produced documents, including 1) the NASEM 2013 Decadal Survey: Vision and Voyages for Planetary Sciences in the Decade 2013-2022, 2) the National Research Council 2007 Report: The Scientific Context for the Exploration of the Moon, 3) the Lunar Exploration Analysis Group (LEAG) Advancing Science of the Moon report, and the NASA strategic knowledge gaps (SKGs) (i.e., explore the history of the Solar System using the Moon, explore processes that shape planetary bodies, use the Moon as a platform for novel and unique measurements, study of lunar volatiles and explore the utility of lunar resources for exploration and beyond). The draft Strategy also includes efforts to engage the community further to develop ideas for science to conduct on the lunar surface. Regarding recent feedback on NASA priorities for achieving lunar science and exploration goals, in February 2019, the Committee on Astrobiology and Planetary Science (CAPS) released two reports that provided findings and conclusions. CAPS concluded that the NASA Lunar Discovery and Exploration Program (LDEP) is aligned with the decadal priorities and the portfolio "is a welcome development that has the potential to greatly benefit lunar science and could evolve into a program with large science return."

Question 12-12a:

You recently decided to cancel the Interior Characterization of Europa using Magnetometry (ICEMAG) instrument in development for the Europa Clipper mission and instead move forward with a simpler magnetometer instrument managed by NASA. It is my understanding that the decision was made after a termination review, and that a new mechanism to monitor costs on PI instruments flagged cost growth on ICEMAG.

a. What, in concrete terms, does the cost-monitoring mechanism do, and how is it being used?

Answer 12-12a:

As a result of continued, significant cost growth and remaining high cost risk, the ICEMAG investigation on the Europa Clipper mission was terminated. NASA is developing a simpler magnetometer with both the fluxgate sensors and boom under the direction of an integrated product manager, has appointed a world renowned magnetometry expert (Dr. Margaret Kivelson, UCLA) as the science team lead, and has retained all ICEMAG Co-Investigators.

Instruments on flagship missions have a long history of cost growth; this process was put into place for Clipper to monitor instrument cost growth in much more detail before it is too late to take corrective action. Before cost margin is completely utilized, descopes or other options are carefully considered by the Project Manager and NASA HQ.

Question 12b:

Are you using it on missions other than Europa Clipper?

Answer 12b:

NASA is considering this process, possibly with some modifications, to be used on other large strategic missions. This can be codified after Clipper experience and lessons learned are realized.

Question 12c:

How have or will you evaluate this mechanism's success as an effective tool for managing cost?

Answer 12c:

NASA currently is gathering lessons on how this new process is working on Europa Clipper, including intended and unintended consequences, which will be used to refine the process. If SMD determines that the process was successful overall, it may be applied to other large strategic missions. If a sufficient database on instrument cost performance is built, SMD will be able to tell if this new strategy is an effective tool for managing cost.

Question 13:

During the question and answer session of the hearing, Congressman Beyer asked you whether or not NASA scientists were going to be required to debate the credibility of the National Climate Assessment, as was reported in Scientific American on June 7, 2019. You responded that you could provide additional information for the record. Will NASA scientists be required to debate the credibility of the National Climate Assessment or otherwise play a role in the White House review of the interagency National Climate Assessment?

Answer 13:

In March, the White House asked the NASA Deputy Administrator to provide "internal scientific peer review of previously published United States Government assessments of climate change and its national security implications." NASA used the opportunity to revisit and evaluate three recent major national assessments of climate change and national security, including the Fourth National Climate Assessment (NCA4), the ODNI Worldwide Threat Assessment, and the Report on Effects of a Changing Climate to the Department of Defense. Drawing on the wealth of Earth science and climate change expertise at NASA Headquarters, NASA responded with detailed internal peer review comments on the three reports.

NASA responded that it has high confidence in the process through which the NCA4 volumes were produced. NASA is a full member and active participant in the interagency U.S. Global Change Research Program, which, under the Global Change Research Act of 1990, facilitates, manages, and publishes the NCA. For the development of the most recent NCA4, completed in November 2018, NASA data, models, and research were integral inputs, and NASA scientists were actively engaged in the drafting and development of the assessment report during its entire production lifecycle, including seeking and acquiring NASA agency approval of the final report. The list of coordinating lead authors, lead authors, review editors and contributing authors demonstrates contributions from many of the most reputable and accomplished scientists working in climate science today. Report findings were based on scientific, peer-reviewed research, and each source of information utilized was subjected to a quality assurance test including the factors of utility, transparency, objectivity, and integrity. They were rigorously reviewed multiple times by experts, including federal and non-federal scientists, the National Academies, and the public. Review editors ensured that all comments resulting from those reviews were fully addressed and formally dispositioned, resulting in reports that meet the rigorous standards pertaining to highly influential scientific products of the federal government, in accordance with the Information Quality Act.

Question 14-14a:

The Sun is expected to reach its next solar maximum in 2024, the administration's new target for humans returning to the surface of the Moon. What do we know about the space weather environment at the Moon during solar maximum?

a. Do you have any concerns about a Moon landing with humans during a solar maximum?

Answer 14-14a:

There are two primary sources of space radiation that require attention relevant to protecting humans as they land on the Moon. They are Galactic Cosmic Rays (CGR) and Solar Energetic Particles (SEP).

Galactic cosmic rays are high energy charged particles from outside the Heliosphere and are the major long-term radiation threat to astronaut's health, and therefore to human space exploration. During solar maximum, because of the increasing strength of the interplanetary magnetic field, the heliosphere provides a more effective shield against galactic cosmic rays. During solar maximum, the flux of galactic cosmic rays is reduced by as much as 50 percent with respect to the solar minimum, depending on particle energy.

Solar energetic particles are generated by coronal mass eruptions and solar flares that are more prevalent during the solar maximum, but may occur at any time. Astronauts on the Moon's surface and in lunar orbit do not have the protection of the Earth's magnetic field and atmosphere, and are at risk of serious radiation exposure should a large solar energetic particle event occur. For the protection of astronauts, a system must be in place to predict, detect, and mitigate hazards of solar energetic particle events.

Question 14b:

What do we need to learn to best protect astronauts from the radiation risks of a solar maximum event?

Answer 14b:

Learning and understanding the dominant mechanism for producing space weather radiation is first step to mitigating the risks to astronauts. Only then can an effective prediction capability be established to protect human explorers in the lunar environment in advance of occurrence of solar particle events. Currently we have only minutes of advanced warning after detection of a solar eruption. Based on our current understanding, we have predictive tools that generate estimates of the likelihood of all clear conditions. Further investigations with missions and modeling of solar energetic particle events will improve our ability to predict their occurrence and thus the capability to signal "all clear" conditions with high confidence and with greater time in advance, during which astronauts are safe from these risks.

Responses by Dr. Chelle Gentemann

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON SPACE AND AERONAUTICS

Discovery on the Frontiers of Space: Exploring NASA's Science Mission

Questions for the Record to:

Dr. Chelle Gentemann
Response credit: Chelle Gentemann with input from CESAS committee

Submitted by Chair Kendra Horn

1. **From your perspective, what is needed to foster multi-disciplinary, interdisciplinary, or high-risk-high-reward science? Are there avenues at NASA for funding such science?**

Multi-disciplinary and Interdisciplinary Science

NASA Research Opportunities in Earth and Space Science (ROSES) is the funding mechanism for NASA competitively selected research. ROSES has specific research calls for interdisciplinary science including an 11.2M program in Earth Science. Interdisciplinary science is also woven throughout more specific ROSES opportunities. However, while these calls enable interdisciplinary science, their effectiveness might be improved by attention to how cloud computing, open source software, and the velocity and variety of data[1] are enabling new opportunities (see Question 8).

An example of interdisciplinary work facilitated by advances in data science is seen in the work of USGS and USAID using high resolution commercial imagery to train classification models to identify cropped area in specific regions. These analyses have allowed for the development of high accuracy agricultural statistics on cropped area and food production in countries that experience frequent food security crises. By extending the availability of commercial imagery that is used together with moderate resolution imagery that is free (Sentinel, Landsat), more accurate agricultural statistics can be generated that will help the USG target these funds effectively, and monitor the results of interventions. It is through data fusion and advanced algorithms that high value information can be generated with satellite imagery, and moving data to the cloud enables this type of work.

NASA is already working towards moving NASA data assets onto the cloud and developing cloud-based platforms to enable scientists to use the data, but this effort could be accelerated. Currently, NASA data is available through data archives and scientists can use internet protocols (eg. OpenDAP) to access subsets of big datasets. To effectively do 'big-data' science, often subsets of data aren't effective, the entire large dataset needs to be available adjacent to computational resources. Once that is

[1] potential of large constellations of smallsats, future instruments, hyperspectral instruments, etc.

in place, the analysis of these datasets for entirely unimagined applications and science is not only possible, but easier and faster.

High-risk-high-reward science

One of the largest impediments to high-risk/high-reward science at NASA is the infrequent and irregular availability of access to space by scientific missions. This significantly lowers the risk tolerance of NASA missions, limiting the use of newer technologies and effectively restricting the scope of the science hypotheses that are tested.

For the science and engineering personnel who lead NASA's larger missions, it is not unusual to only have involvement with a few missions over the course of one's entire career. Given such limited opportunities, high risk options are often watered down or avoided altogether to produce mission objectives and success criteria that are more easily achieved. These constraints could be overcome or significantly mitigated by more frequent launch opportunities that occur on a regular schedule.

The recent growth in micro-satellite technology is one promising enabler of this capability. The smallest CubeSat versions have standardized many of their components, significantly aiding in their growth and popularity with Universities and Industry. The same standardization is needed with larger micro-satellites that are capable of addressing more difficult science investigations, and NASA should play a leading role in defining those standards.

Along with smaller satellites, smaller and cheaper launch vehicles are also needed, and the mechanical, thermal and electrical interface requirements between them and the satellites also need to be better standardized. Given more and cheaper rockets and satellites, a regular and reliable schedule of launch opportunities for science missions could be established. With that in place, the scientists and engineers who design those missions would take more risks in pursuit of greater rewards.

2. **In response to a question from Chairwoman Johnson, you testified that "China is launching Earth-observing satellite after Earth-observing satellite and working with Europe to establish leadership." Could you expand further on your perspectives on the overall state of Chinese space and Earth sciences and the implications of those activities for NASA's Earth science activities?**

The 2017 Earth science decadal survey states, "In a time of constrained resources, access to all data, including from nations such as China, can enable a more robust U.S. program at a lower cost to the U.S. Those opportunities go unrealized when there are restrictions on Federal agencies regarding engaging China and making use of their assets." China has a vibrant, robust research program in Earth Science. Non-NASA researchers around the world benefit by using China's satellite observations and participating in collaborative research on weather and climate. Modern weather forecasting relies on international data sharing agreements that benefit all parties.

The international sharing of data has extended forecast lead times and improved accuracy. NASA and ESA have an open data policy, and are pushing for open science and open source research software. For many science researchers, myself included, software and research are open from inception and freely available on GitHub to anyone. The pace of scientific advancement increases with open data, open science, and open source software, and everyone benefits from these open policies. These open policies have also created substantial opportunities in multi- and inter- disciplinary research.

3. **What issues and opportunities have the Committee on Earth Sciences and Applications from Space discussed related to NASA's pilot commercial data buy program?**

CESAS has not discussed the NASA pilot in detail, but in preliminary discussions some members have noted that scientific evaluation process can be significantly hampered if non-disclosure agreements have to be signed as they prevent discussion of the results with anyone other than the commercial data provider. It was also noted that most journals require data to be publicly available in order to publish any scientific results.

Several private data sources are being evaluated by a broad set of NASA researchers to determine the value of the geophysical information for advancing NASA research and application objectives. We expect to be briefed on the results of this project at the CESAS Fall 2019 meeting and the committee stands ready to assist NASA with studies or workshops as requested.

4. **A common tenet reiterated in the decadal surveys is the importance of "balance." What does "balance" mean, and why is it important? What are the signs a program is in or out of balance?**

The importance of a balanced program in optimizing the use of scarce resources is reflected in the Earth science decadal survey's "statement of task" (SOT). NASA inserted into the SOT the following:

> For NASA, the committee will pay particular attention to prioritizing and recommending balances among the full suite of Earth system science research, technology development, flight mission development and operations, and applications/capacity building development conducted in the Earth Science Division (ESD) of the Science Mission Directorate. In particular, while making clear its assumptions regarding the overall scope of the NASA ESD program relative to the contributions of the mission agencies NOAA and USGS, the committee will make recommendations on:
>
> a) The target budgetary balance between Flight and Non-Flight aspects of the ESD portfolio;
>
> b) In the Non-Flight portion of the program, the target balance between R&A, Applied Science, and Technology elements;
>
> c) In the Flight element, the target budgetary balance between systematic/directed, and competed/cost/schedule-constrained mission programs;
>
> a) In the Flight element and considering overall resource constraints, the target budgetary balance between general mission-enabling investments (such as common spacecraft development, highly

disaggregated constellations, etc.) and traditional focused single-mission developments;
b) In the Flight and Technology elements, the degree that NASA investment decisions could be informed by NOAA and USGS operational satellite measurement objectives,;
c) Expanding or modifying the present 3-strand Venture-Class competed program, including examining whether ESD should initiate additional or different Venture Class strands, possibly with different cost caps;
d) Decision principles for balancing new measurements against time series extensions of existing data sets; and
e) Any changes in scope(s) of the non-flight R&A, Applied Sciences, and Technology Development elements.

"Balance" is evidently a nuanced topic and it is discussed in detail in, "NASA Programmatic Balance and Scope," a section of chapter 4 of the decadal survey report (http://nap.edu/24938) that is appended to my QFR responses. Importantly, the decadal survey's bottom line was, "The current balance ... is largely appropriate, enabling a robust and resilient Earth science program, and can be effectively maintained using decision rules such as recommended in this report."

At NASA ESD, a key issue is the optimization of allocations among hardware--primarily building and launching satellites--and research and analysis-related accounts that focus on the exploitation of existing data from current missions. ESD tries to keep the R&D budget at 24% of their total budget, with about 60-70% going to new missions and mission operations. As discussed in the ESAS report, issues of balance also arise within the flight element of ESD as trades are made among smaller, less expensive, more frequently available but typically more focused missions, and larger, more expensive and often multi-instrument missions that can cost-effectively address science issues of concern to a broader community and/or address issues that require instruments not suitable for smaller platforms.

While the decadal survey was largely supportive of the current balance across and within ESD programs, one should recognize that needs may change over time; for example, regarding the balance between discipline specific science and interdisciplinary science, or perhaps the boundaries between them.

5. To what extent has the Earth Science community identified any issues regarding large satellite constellations and interference with Earth Science measurements or observations?

The most critical issue related to interference with Earth Science measurements and observations is appropriate management and use of the radio wave spectrum. Specific portions of the spectrum are required to make proper measurements of atmospheric molecules and necessary observations of the Earth system. These frequencies are dictated by the laws of quantum mechanics and cannot be changed. Transmission in those parts of the spectrum can and do interfere with the Earth Science measurements, whether the transmitters are located on the ground and transmitting up or in space and transmitting down. Effective management of the radio wave spectrum requires two things. One is proper identification of those parts of the spectrum that must be protected, by the FCC and other relevant agencies. The other is proper enforcement of restrictions on transmission within the protected bands.

6. **In your prepared testimony, you reference the 2018 Earth science decadal survey's highest priority, which is completing the Program of Record (POR). You also spoke about the recommendations from the 2007 inaugural decadal survey for Earth science and applications from space during the question and answer session of the hearing. Can you clarify the relationship and distinction between the POR and the 2007 survey recommendations?**

The current POR reflects the priorities of the 2007 survey, but it is not a one-to-one mapping for many reasons, including: assumed budgets that did not materialize, missions that expanded in scope or overran their budgets, as well as changes that flowed from a better understanding of technology challenges and cost, the potential to leverage international partners, and directives from Congress or the Administration.

7. **The Chairwoman of the House Science, Space, and Technology Committee, Ms. Johnson, and the Ranking Member, Mr. Lucas, sent a letter to the FCC urging a reexamination of the 24 GHz spectrum auction after concerns were raised by NASA and NOAA about potential interference with Earth observations for weather forecasting. What are your perspectives on that particular band, and radiofrequency issues more broadly, for space-based Earth science data?**

There is substantial concern from the scientific community about the impact of allowing commercial transmissions near the 23.8 GHz frequency. The NASEM's Committee on Radio Frequencies (CORF), which serves as the U.S. representative to int'l organizations concerned with frequency allocation issues, has two recent reports entitled "Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses" and "A Strategy for Active Remote Sensing Amid Increased Demand for Radio Spectrum", regarding the principles for the allocation and protection of spectral bands for services using the radio spectrum for scientific research. This issue concerning 24 GHz needs more study to understand exactly what the effects on science will be.

8. **During the question and answer session, you stated that we are "right at the cusp of a very exciting time in science where how science is being done is being reorganized" because of advances in technologies like cloud computing and the ideas of open science. Could you expand further on what kinds of new science questions can be answered due to this shift, and why? What are the considerations for NASA in the era of big data in terms of workforce, resources, technology, and how NASA does science generally?**

The types of questions that scientists ask can be subtly influenced by what they think they can answer. For scientists, simply being aware of what data or model is available can influence what possibilities they can imagine and this can hinder the big leaps or breakthroughs in understandings that truly advance science. Advances in open source libraries are occurring rapidly enabling faster, better science. As science moves to the cloud, a revolution in how we use data is occurring. How scientists collaborate is changing and interdisciplinary science is resulting in new applications for societal benefit. The reproducibility of science is being enabled in a manner that was unimagined 3 years ago. This shift is resulting in me spending less time trying to get my results and more time thinking about my results and how to extend them. That is why this shift is changing science and why it is exciting.

NASA data is distributed to data archives that require people, stability, and resources. There are amazing employees at NASA data centers who are working to move NASA data to the cloud, but there aren't enough resources to push forward this transition by engaging external resources, maintain the necessary backbone of data access, and provide funding to explore new science on the cloud. This is an opportunity where I feel that directed funding could have immediate, outsized, benefits, and position NASA for future major scientific advances.

For example, it is likely that within only a few years, the constellations of smallsats will grow in size, from tens to hundreds to thousands, and everything from autonomous operations to value-added ground processing will benefit from AI, cloud computing, open source software, and open data access. All these new data are forcing different communities to interact, again enabling interdisciplinary science. We need to be prepared for this new data and computing paradigm if we want to remain at the forefront of science and benefit from all the advantages (economically, socially, geopolitically, and on security) that such a position entails.

Responses by Dr. David Spergel

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July 15, 2019

Dear Chairwoman Kendra Horn:

I am writing in response to your letter of July 1, 2019 requesting my response to questions from the committee. I want to begin by thanking you and the committee for the opportunity to address you in June and want to thank you for your efforts.

I have no corrections to the transcript of the hearings,.

I address the questions for the record below:

1. *From your perspective, what is needed to foster multi-disciplinary, interdisciplinary, or high-risk-high reward science? Are there avenues at NASA for funding such science?*

   The NASA is very good at supporting high quality low risk science analysis and missions. The process of selecting missions and the process of mission development selects for projects that are likely to succeed. The incentives both internal to the NASA labs and within the agency reward success and punish failure. Even when the NASA leadership pushes for innovation, there is resistance within the culture. Similarly, the grant review process is relatively conservative and tends to support approaches that have a high probability of success. No one wants to "waste" money. Unfortunately, the process often fails to support the high risk/high return research. Multi-disciplinary and interdisciplinary research falls "between the cracks". High risk science fails to be ranked highly in a competitive review.

   I believe that a possible solution to this problem would be for NASA to explicitly dedicate a modest fraction of its research budget to "high risk" research. It could establish a dedicated grant call for this purpose. If researchers knew that they were proposing to a "high risk/high reward" grant competitions, they would be encouraged to propose projects that could be truly transformative.

2. *Organizations such as the International Astronomical Union, the National Radio Astronomical Observatory, the Associated Universities for Research in Astronomy and the American Astronomical Society have expressed concerns on the effects of large satellite constellations on the night sky. The number and size of satellite constellations are likely to grow significantly in the coming years; what are the considerations for scientific research, given that reality, how is the scientific community engaged on the issue?*

   SpaceX's recent launch of the first of the Starlink Satellite constellation has generated significant concern in the international astronomical community. The satellites in these constellations can appear as bright as some of the brightest stars in the night sky. These satellites can also be strong sources of radio and microwave emissions. I agree with the recent AAS position statement on these constellations. I believe that it will be important to create fora where astronomers and space technologists can identify ways of deploying satellites and limiting their visual impact on our night sky. By directly reflected stellar light away from the Earth, it is possible to significantly reduce the visual impact of these next generation commercial satellites.

3. *What kind of new or cross-cutting science might be possible in the era of "big data" and what would be needed to enable such science? What are the considerations for NASA in the era of big data in terms of workforce, resources, technology and how NASA does science generally?*

   Most of our traditional statistical techniques are designed for the analysis of linear relationships between low dimensional data. Most scientists have been trained to fit "y=ax+b" to simple data with well modelled noise properties. However, many of the systems studied by NASA (e.g., the atmospheres of Earth, stars and planets or forming galaxies) are highly non-linear processes in multidimensions that cannot be described fully by simple models.

   The past decade has seen a revolution in machine learning and data science. These advances have enabled new tools for describing data in very high dimensional spaces. These techniques are only beginning to be applied to NASA data. For example, techniques developed for processing images of faces in Facebook could yield new insights when applied to astronomical images. Personally, I see these new techniques as the most promising new approach to modelling complex non-linear systems and have made this area the focus of my own recent research.

   For NASA to fully exploit these advances in data science, it will need to reach out and support scientists and engineers drawn from communities that do not normally participate in NASA-supported research. NASA will need to encourage data scientists and computer scientists to work together with "domain experts" in space science to develop novel approaches. It will need to support more interdisciplinary work and find avenues to support teams that take non-traditional approaches to data modelling.

   NASA should encourage students pursuing PhDs in space science-related fields to learn these new techniques through summer schools and encourage the development of graduate programs that span these fields. Many universities are developing new programs in data science. Data science and computer science are the fastest growing majors at many universities. Because NASA has very large publicly available data sets, it can provide a superb training ground for these students. By encouraging these students to work with NASA data, we will not only gain new scientific insights but help train a workforce that will benefit both science and the rapidly growing data science industry.

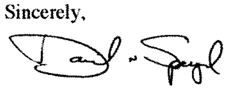
4. *A common tenet reiterated in the decadal survey is the importance of "balance". What does "balance" mean and why is it important? What are the signs that a program is in or out of balance?*

   Balance is a multi-dimensional concept. When decadal surveys speak of balance, they are discussing balance between mission size, balance between scientific subfields, and balance between technology development for future mission, development and construction of missions, mission operation, and analysis of multi-mission data. If we shortchange technology development, we will not have the capabilities for future novel missions. If we fail to fully fund missions in development, their costs will spiral out of control. If we fail to properly fund analysis and theoretical interpretation, then we will fail to exploit the scientific value of our missions. Because missions of different scales serve different roles, it is important that we build both explorer probes (e.g., WMAP, TESS, SphereX) that produce focused science and train the next generation of instrumentalists and large facilities (e.g., HST) that can be used to study a wide range of scientific questions.

Because overruns in large projects can have major budgetary impacts, they are most likely to skew the balance across mission sizes and scientific development stages. I would be concerned if the costs of large missions (averaged over a few years) exceeds more than 2/3 of a directorate's budget. Unless new resources are being brought into the budget, this will likely suffocate technology development, the construction of smaller missions, and analysis and operation of current missions and their data. On the other hand, if we are only investing in smaller missions, then we are unlikely to see transformative results across the field nor are we likely to be pushing the technological envelope.

Thank you for the opportunity to address these questions.

Sincerely,



David Spergel
Charles Young Professor of Astronomy, Princeton University
Director, Center for Computational Astrophysics, Flatiron Institute

Responses by Dr. Mark Sykes

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON SPACE AND AERONAUTICS

Discovery on the Frontiers of Space: Exploring NASA's Science Mission

Questions for the Record to:

Dr. Mark Sykes

Submitted by Chairwoman Kendra Horn

1. From your perspective, what is needed to foster multi-disciplinary, interdisciplinary, or high-risk-high-reward science? Are there sufficient avenues of support for such science at NASA?

ANSWER:

I believe the avenues for such support exist in NASA's planetary program. Some programs like the Solar System Exploration Research Virtual Institute (SSERVI) promote "cross-discipline partnerships", and there is nothing barring such partnerships in other research programs (NASA has a record of trying to make such partnerships work across programs when a good case is made). However, I feel the ability to recognize high-risk-high-reward science proposed to planetary research programs is degraded. This could be better assessed if there were transparency in review panel composition, directives, and other statistics.

2. How significant is the science ofChang'e-4, the Chinese probe that recently landed on the far side of the Moon? What are your perspectives on the overall state of Chinese space sciences?

ANSWER:

The observation of potential mantle materials by the Near Infrared Spectrometer on the Yutu 2 rover could be important. Other science results from Chang'e 4, are still to be released, and are also potentially valuable. This includes the deployment of three 5-meter long booms in preparation to make the first low-frequency radio observations from the quiet far-side environment (a long-time goal of radio astronomers), and other experiments. At this point in time, the significance of the Chinese space science program is its demonstration of technical capabilities.

Very impressive was their being the first country to land on the far side of the Moon, and their placing a communication satellite in Earth-Moon L2 to allow for communication between the lander and the Earth - something no one else has done. This was presaged by Chang'e 2 operations around L2 after mapping the surface of the Moon and before departing lunar orbit to flyby the NEO Toutatis. Chang'e 4 will be followed by the Chang'e 5 lander mission, which will return a sample to Earth from Mons Rümker, a volcanic formation in the northern part of Oceanus Procesllarum. More robotic missions to the Moon are planned through the 2020s, and a manned lunar mission and potential base are also contemplated for the 2030s.

China is planning to launch a Mars orbiter and lander/rover together in the summer of 2020, with a potential sample return later in the decade. This builds on their prior Yinghuo-1 probe, which was lost when the Fobos-Grunt mission with which it was co-manifested failed to leave Earth orbit in 2011. They are planning an NEO sample return mission in the next decade and are interested in the space-based survey of the population of NEOs. Two other major targets in the 10-20 year timeframe are Venus and Jupiter.

I cannot speak to its astrophysics ambitions in space.

China has demonstrated sophisticated home grown engineering and operational capabilities in its Chang'E program. At the same time, China recognizes that it needs to heavily invest in the education of future scientists if they are to gain benefit from their ambitious space science program - even moreso when covering well-trodden ground, where achievement is no longer measured in just reaching a destination.

Their space science bench is currently behind the US, but we have been investing in space science for more than 50 years. They are leveraging what we and others (particularly Europe) have learned over this time. They are hiring knowledgeable and talented scientists to teach and conduct research at their universities (the University of Hong Kong hired away one of PSI's well-known Mars scientists). Our science mission data has been available to everyone for decades, and the Europeans have been following our example, so they have good information to work and learn with.

In my testimony, I said we should be looking at China as a potential partner (in space science). I would revise my statement by removing the word "potential". In Beijing, I have met and had discussions with people involved in their solar system exploration program. There are a lot of young engineers, and they exude pride in what they have accomplished - as well they should. We do the same! They want to be the best in what they do, and for that to happen, science requires openness and the ability to freely exchange information and ideas. This can be difficult in a political system where the flow of information and ideas are throttled. All the more reason for us to partner with them. Yes, there are important security issues always, but they are manageable, and we will also learn and benefit from them. It is a two-way street.

It is in our national interest that the Wolf amendment should be relaxed, if not removed.

3. In both your prepared testimony and your responses during the question and answer period, you stated that a complementary space- and ground-based approach to finding the potentially hazardous asteroids should get us to the Congressionally-mandated 90% completeness for objects larger than 140 meters. What other actions are needed to malce progress on mitigating the risks of potentially hazardous near-Earth objects?

ANSWER:

I noted in my opening statement that at the Planetary Defense Conference last May, Administrator Bridenstine announced NASA was moving forward on the NEOCam mission, which the National Academies had recently determined would be the fastest way to meet the Congressional mandate (and they recommended such a mission proceed). However, a news report on July 5, 2019, quotes a "NASA spokesperson" as saying "The Planetary Defense Program at NASA does not currently have sufficient funding to approve development of a full space-based NEO survey mission as was proposed by the NEOCam project." (https://qz.com/1659566/nasa-nixes-hunt-for-deadly-asteroids/).

If this Administration is going to take planetary defense at all seriously, then NEOCam must be adequately funded and properly managed. The single most important thing we can do to mitigate the risk of NEOs is to assess the hazard, which means finding them. It is silly to invest hundreds of millions of dollars in a mitigation experiment (i.e., DART), and not place at least the same priority on finding the objects that might hit us, to which the mitigation strategy might be applied.

NEOCam was originally proposed as a science mission, and was very highly ranked in the last Discovery call. However, it was primarily designed to achieve the Congressional planetary defense goals, as well as provide information essential for future in-situ resource utilization in space and identifying targets for human exploration more accessible than lunar orbit. Now that NEOCam is considered a planetary defense mission, I worry about arbitrary reductions in budget with changing mission focus - a time-honored habit of the agency, which I see often on Senior Review panels for extended missions. This can (and often does) translate to degraded mission performance and reduced capability to fully achieve desired objectives.

For NEOCam, when shifting from curiosity-driven science to applied science objectives (i.e., planetary defense) the design of the telescope, the detectors, and the cadence of observations do not change. Therefore, the cost should not change. I note that NEOCam has a very mature cost model, because it has been through the Discovery process four times, including three Step 1's and one Step 2 round.

Once NEOCam is successfully launched, and the characterization of the NEO population is well-underway, the next actions needed to make progress on mitigating the risks of potentially hazardous near-Earth objects will be numerous mitigation experiments.

Near-Earth Objects come from a wide range of locations in the main asteroid belt and beyond (even out to the Kuiper Belt). They necessarily have wide-ranging collisional histories. All this translates to the fact that NEOs cannot be assumed to have the same physical and mechanical properties. As a consequence, the results of, say, an impact experiment on one cannot be expected to be reproduced when conducted on a different object. Multiple experiments on multiple targets will be required to gain any confidence in a particular mitigation strategy to deploy when we are faced with a target that is going to hit us.

The many targets that NEOCam will provide will not only be necessary for multiple mitigation experiments needed, but will be necessary to reduce their costs.

4. During the question and answer period of the hearing, you stated that you would not want "people to be busting the budget by borrowing from Peter to pay Paul" in response to a question about incentivizing cost-effective management of principle-investigator-led missions by allowing Pls to use surplus funding from mission development for research by the science team. Could you please expand on your comments?

ANSWER:

Thank you for the opportunity to expand my comments on this subject.

It is my understanding that money saved in mission development cannot be spent years later for science when the spacecraft reaches its target (unless that target is the Moon or perhaps Mars). However, implicit in the question is a recognition that mission science is generally underfunded. It is.

Part of this flows from our basic approach to missions. We generally set minimal science goals for a mission in order to maximize the possibility of the mission being 100% successful. These are generally referred to as Level 1 Requirements.

There are three circumstances when more mission science can be defined: (1) at mission selection, since such additional science is likely already known by the science team, (2) at the mission target when data is acquired resulting in new discoveries and new ideas, and (3) when the mission can continue to operate beyond its nominal lifetime. In each of these situations, the question asked should be given the system to be flown, what is the maximum science that can be returned where an assessment of the marginal cost concludes it would be well-worth the investment. These are the times when funds to support additional science should be made available. It should not depend upon whether mission development costs came in under budget.

Science is the return on taxpayer investments in our missions. We should always be working to figure out ways to maximize that return.

Something similar to the Senior Review process for extended missions might be utilized for assessing the value of the proposed additional science weighted byits cost in (1), (2), and (3). I would recommend this without the artificial constraints imposed by imposed guideline budgets, which are a feature of the extended mission reviews. This might be funded through additional budget to be included in mission program lines. Costs associated with circumstances (1) and (2) would be modest, since it would be almost exclusively science team expansion and support. Circumstance (3), extended missions, are more expensive because it also includes extending the operational costs of the mission.

At present I am concerned about a worrisome trend of reducing mission science team support. The idea is to rely increasingly on delivery of data to the NASA Planetary Data System, then depend upon data analysis programs to support the science obtainable from the data. This is bad at a variety of levels. Science in real time can have an impact on spacecraft operations, particularly when a discovery or novel insights are made at the target object. It affords an opportunity to combine data sets by different instruments to understand what is going on. Data analysis programs do not fund "fishing expeditions" - you have to pretty much know what you will be finding at the beginning. Published science out of a data analysis program can also be more than three years after data acquisition (acquisition→archiving→proposal submission→proposal selection→funding award→research effort→time to publication). This also cuts out the opportunity above for more science under circumstances (1) and (2) and necessarily weakens a case for (3).

5. A common tenet reiterated in the decadal surveys is the importance of "balance." What does "balance" mean, and why is it important? What are the signs a program is in or out of balance?

ANSWER:

In the planetary decadal survey there are different portfolios: Large directed missions (flagships), competed missions (New Frontiers and Discovery) that are cost-capped, and research/data analysis programs and technology programs. Within a decade, a balanced program among these portfolios consist of 1 flagship mission, 2 New Frontiers missions, 5 Discovery missions, a healthy research and data analysis program (most recently with a defined budget profile) and a healthy technology program (most recently with a defined budget level as a fraction of the overall Planetary Science Division budget). A limited number of flagship missions are defined and prioritized. Although competed, a list of acceptable New Frontiers missions are defined, but not prioritized (this should be modified to allow other missions, making the case on the basis of new discoveries made since the decadal release). Discovery missions are unconstrained.

A diverse mission portfolio allows for diverse science to be pursued, and a regular cadence of missions that allow us to sustain our capabilities as a nation in solar system exploration. Research and data analysis programs and technology programs are the foundation on which our missions are defined and developed. These are also essential to sustaining our capabilities and training the next generation of planetary scientists and engineers.

Having a balanced portfolio is fine, but it is absolutely critical to have rules to follow when budgets are unable to support a balanced portfolio. In my opinion, the most important recommendation of the recent planetary decadal survey was:

"It is also possible that the budget picture could turn out to be less favorable than the committee has assumed. This could happen, for example, if the actual budget for solar system exploration is smaller than the projections the committee used. If cuts to the program are necessary, the committee recommends that the first approach should be descoping or delaying Flagship missions. Changes to the New Frontiers or Discovery programs should be considered only if adjustments to Flagship missions cannot solve the problem. And high priority should be placed on preserving funding for research and analysis programs and for technology development."

Balance is regularly threatened and often undermined due to cost overruns in directed missions, primarily flagships. The Discovery program was decimated for more than a decade after 2000. In an extreme example in 2006, planetary research programs were cut (and Astrobiology gutted) to support the continued development of the Crewed Exploration Vehicle and Crew Launch Vehicle. Today, cost overruns associated with Mars 2020 are being covered by other missions (there is no transparency regarding the size of the overruns and what programs are specifically being impacted).

Maintaining balance within the NASA planetary science program (and perhaps other divisions as well) requires Congress to forbid NASA from transferring funds from competed missions and research programs to non-competed, directed missions (like flagships). Instead of hiding these cost overruns when they arise, if NASA cannot find solutions within the portfolio of directed programs, it should go back to Congress and make the case for more funds.

Appendix II

ADDITIONAL MATERIAL FOR THE RECORD

ADDITIONAL RESPONSES SUBMITTED BY DR. THOMAS H. ZURBUCHEN

Material requested for the record on page 70, line 1622, by Representative Waltz during the June 11, 2019 hearing at which Dr. Thomas Zurbuchen testified.

Question:

If you could submit for the record how the Mission Directorate partners with STEM Institutions like Embry-Riddle for research and development.

Answer:

NASA's science vision is to use the vantage point of space to achieve with the science community and our partners a deep scientific understanding of the Sun and its effects on the solar system, our home planet, other planets and solar system bodies, the interplanetary environment, and the universe beyond. Key to our success is fulfilling our commitment to improve people's lives today and to inspire and engage the workforce of tomorrow. At every step, we share the journey of scientific exploration with the public, and partner with others to substantially improve science, technology, engineering, and mathematics (STEM) education nationwide.

Specifically, SMD partners with Embry-Riddle Aeronautical University through a variety of research projects, most of which are funded through the Heliophysics Research and Analysis (R&A) program. There are also projects funded through the Earth Science R&A, Planetary Science R&A, Discovery Research and Guest Investigator programs. Below is a list of some recent projects.

Science Mission Directorate:

- Dynamics of the E and F regions of the ionosphere and their impact on radio communications using sounding rockets –
  Program: Heliophysics Technology and Instrument Development for Science (HTIDS) which is part of Heliophysics Division R&A
  5/19 to 4/22
  $1.3 million awarded
  PI = A. Barjatya

- Theoretical and modeling study of the behavior of Earth's ionosphere, augmented by Themis and CLUSTER data
  Program: Heliophysics Division R&A Supporting Research (HSR) Program
  Project dates: 5/17 to 9/20
  $750k awarded
  PI = K. Nykyri

- Solar wind interaction with Earth's magnetosphere at the magnetopause using Themis and Magnetospheric Multi-Scale (MMS) observation data along with simulation models
  Program: Heliophysics Division R&A Supporting Research (HSR) Program
  Project dates: 8/18 to 67/21
  $635k awarded

PI = X. Ma

- Source of high energy electrons in Earth's magnetosphere at various times of year, and improving interpretation of MMS data –
  Program: MMS Guest Investigator
  Project dates: 8/18 to 7/21
  $522k awarded
  PI = K. Nykyri

- Use of GNSS/GPS satellite network measurements of total electron content of Earth's ionosphere and 3D models to understand the ionosphere and thermosphere responses to acoustic and gravity waves
  Program: Heliophysics Division R&A Supporting Research (HSR) Program
  Project dates: 7/18 to 6/21
  $485k awarded
  PI = J. Snively

- Impact of earthquakes and volcanos on the ionosphere through acoustic and gravity waves using models and GPS measurements, improve interpretations of measurements of waves in the ionosphere caused by volcanic or seismic forcing
  Program: Earth Science Division R&A
  Project dates: 9/14 to 9/18
  $302k awarded and obligated to Embry-Riddle
  PI = J. Snively

- Use of Themis and Artemis data in a statistical study of interactions between the solar wind and Earths magnetosphere
  Program: Guest Investigator
  Project dates: 3/16 to 7/20
  $371k awarded and obligated
  PI = K. Nykyri

- Measurements of Sodium and Potassium in the lunar exosphere to better understand the composition, sources, sinks, and escape of the lunar atmosphere, measurements occurred during the NASA Lunar Atmosphere and Dust Environment Explorer (LADEE) mission
  Programs: Planetary Science Division R&A and Juno
  Project dates: 8/15 to 7/19
  $201k awarded and obligated
  PI = E. Mierkiewicz

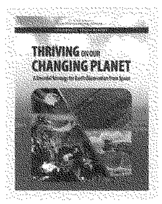
- Reconstruction of Ion Outflow Using VISIONS ENA Measurements – outflow of ions from the ionosphere (top of Earth's atmosphere) using sounding rockets and modeling, how particles from our atmosphere are "leaking" into space
  Program: Heliophysics Division R&A
  Project dates: 5/15 to 4/19

$120k awarded and obligated
PI = M. Zettergren

- Development of models for use with VISIONS-2 sounding rocket campaign data, which measured ion leakage from the top of Earth's atmosphere
  Program: Heliophysics Division R&A
  Project dates: 2/16 to 4/20
  $93k awarded and obligated
  PI = M. Zettergren

- Use of the WISE (Wide-field Infrared Survey Explorer) for solar system dust measurements and asteroid characterization
  Program: Discovery Research
  Project dates: 12/17 to 12/18
  $37k awarded and obligated
  PI = A. Kehoe

REPORT SUBMITTED BY DR. CHELLE GENTEMANN



Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space (2018)

DETAILS

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nonprofits, and the defense community.[8] Technology investment in sensors, low size, mass and power electronics, small satellites, small launch vehicles, and secondary payload and rideshare transportation elements remain critical. When possible, such technology investments should be made through competitive means, potentially in partnership with NASA's Space Technology Mission Directorate.

Within NOAA flight programs, GOES-16 and JPSS-1 both benefited from block buys of instruments and spacecraft, with an expected service life continuing through the time frame covered by this decadal survey. However, system replenishment in the following decade (2028-2037) will require decisions and investments in this decade in order to maintain and potentially improve the quality of the data used for both research and operational forecasting. These systems have significant positive impact on U.S. economic competitiveness, national security, and quality of life. The National Environmental Satellite Data and Information Service (NESDIS) plan is to "develop a space based observing enterprise that is flexible, responsive to evolving technologies and economically sustainable" (Volz, 2016) by moving away from stand-alone space and ground programs and identifying low-cost and rapidly deployable space systems that meet future needs.

While this committee agrees with the NESDIS strategic goal, we suggest an incremental approach in which commercial system and data opportunities demonstrate an "equal or better" performance baseline established by existing GOES and JPSS systems, as suggested in the NESDIS Independent Review Team report (IRT, 2017). This risk of moving to new commercial systems must be balanced against the technology availability risk of these legacy systems, particularly in areas related to critical sensor technologies.

The continuity needs of Landsat data products also suggest that USGS implement a balanced strategy that weighs moving toward commercial systems and employing innovative approaches to advance system capability and reduce cost against the technology availability risk of legacy systems. As such, the committee suggests that both NOAA and USGS make the needed investments in both existing and new technologies to ensure the sustainment and improvement of the measurements required for weather forecasting and continuation of critical climate measurements. In the coming decade it is expected that each of these critical Earth observing systems will move toward further use of commercial systems and data opportunities, while the importance and benefit of federal investment in space technology will continue to increase.

NASA PROGRAMMATIC CONTEXT

NASA's contextual issues range from programmatic balance to technology innovation. Successfully addressing each of these topics is essential to effective implementation of the ESAS 2017 science and applications priorities and associated observation plan.

NASA Programmatic Balance and Scope

The NASA Earth Science Division (ESD) has a broad mandate to develop measurement technology, to advance scientific discovery, to apply measurements and science for societal benefit, and to educate and inspire citizens and a next generation of scientists. Within its budget, NASA ESD must seek an optimal balance to achieve this broad mission in the most effective and efficient way possible. NASA ESD must support a world-class scientific research program that will both guide the development of the missions and will fully realize the value of the resulting data. While developing improved technology and addressing

[8]One critical trade-off is between "block buys" (purchase of multiple instruments or spacecraft to achieve cost savings) and technology advances. Block buys can reduce cost, but they constrain the ability to leverage newer technologies as they arise within the time duration of a block.

novel science questions, NASA also must optimally utilize its existing fleet of satellites that continue to collect important data.

In addition to scientific discovery, NASA has a congressionally directed mission to monitor the stratosphere, and is also the de facto agency responsible for continuing satellite measurements critical to climate science (see the discussion of agency roles in the "Toward a National Strategy" section of Chapter 2). It is also important for NASA to foster the translation of this information to societal benefit through applications of the data, partnering with operational agencies and transferring mature tools to these agencies.

Robustness and Resilience

A major purpose of striving for balance is to achieve programmatic robustness and resilience. To guide the balance discussion, the committee identified characteristics of a robust and resilient observational program, including both flight and nonflight issues.

Finding 4.4: A robust and resilient ESD program has the following attributes:

- A healthy cadence of small/medium missions to provide the community with regular flight opportunities, to leverage advances in technologies and capabilities, and to rapidly respond to emerging science needs;
- A small number of large cost-constrained missions, whose implementation does not draw excessive resources from smaller and more frequent opportunities;
- Strong partnerships with U.S. government and non-U.S. space agencies;
- Complementary programs for airborne, in situ, and other supporting observations;
- Periodic assessment of the return on investment provided by each program element; and
- A robust mechanism for trading the need for continuity of existing measurement against new measurements.

Elements of an Overall Balanced Program

A properly balanced program needs to reflect multiple aspects of balance. In general, these aspects cannot be viewed in isolation. Doing so may result in optimal balance for that particular aspect of the NASA program, but suboptimal balance for the program as a whole. The important aspects of NASA's overall balance are discussed in this section, with specific topics regarding the flight program covered in the following section.

Balance Between Flight and Nonflight Elements

Figure 4.1 shows the annual ESD expenditures for flight missions and mission support from 1996 to 2017. This figure shows actuals through 2016 and estimates, based on a simple inflation adjustment, during the decade 2017-2027. Total expenditures in constant dollars are currently about 75 percent of expenditures in the late 1990s. In recent years, the ratio of flight to nonflight expenditures has been about 60 to 40 percent. The number of beneficial Earth observations that NASA ESD can make has expanded, but the purchasing power of its budget has declined.

Balance Between ESD Program Elements

Figure 4.2 shows detail on how NASA-ESD expenditures (since 2007) are apportioned among six program element categories. The total ranges of these categories are given in Table 4.2. The proportions have been fairly constant in recent years.

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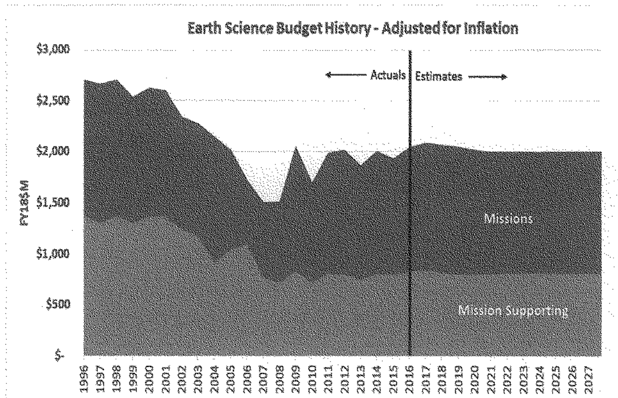

FIGURE 4.1 The NASA Earth Science budget 1996-2016+ ($ FY 2017), showing both mission and nonmission contributions. For the period following known budget requests, a simple inflation-adjusted increase is assured.

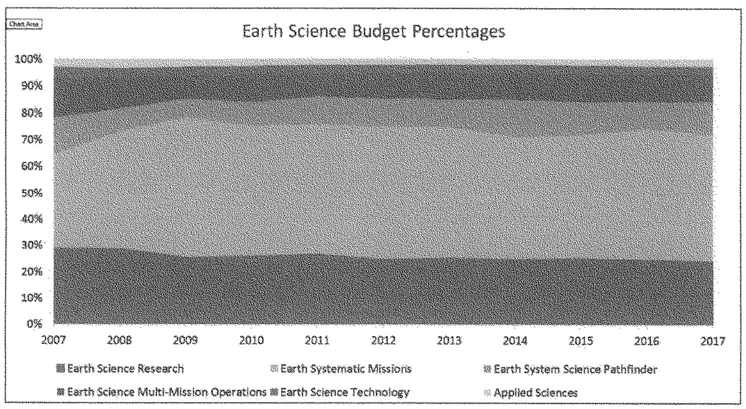

FIGURE 4.2 Percentage of Earth Science Division (ESD) budget devoted to Science Research, Systematic Missions, Earth System Science Pathfinder missions (includes Venture), Multi-Mission Operations, Technology, and Applied Sciences from 2007 to 2017.

TABLE 4.2 Percentage Ranges of Expenditure Categories Since 2007

Expenditure Category	Low %	High %
Earth Science Research	24	29
Earth Systematic Missions	35	52
Earth System Science Pathfinder	7	14
Earth Science Multi-Mission Operations	9	14
Earth Science Technology	3	5
Applied Sciences	2	3

Figure 4.2 and Table 4.2 show that since 2007 a large fraction of the budget has been spent on systematic missions. In 2016 about 47 percent of the budget is for large missions and 12 percent for Earth System Science Pathfinder and Venture missions. Large directed missions are justified if they are needed to address a particularly difficult but important problem, or to collect the complement of measurements needed to address critical interdisciplinary problems (NASEM, 2016a). However, an appropriate balance for the broader community also requires a cadence of opportunity for principle investigator (PI)-led and Venture class missions that is frequent enough to sustain a culture of innovation and creativity among the Earth observations from the space community.

Balance Between Mission Investment and Science Investment

As stated previously, a balanced NASA program requires a strong scientific research and applications program to plan and utilize remote sensing measurements of Earth. In 2016 about 18 percent of the total ESD budget was directed toward Earth Science Research and Analysis; 3 percent to computing, including the across-NASA High-End Computing Capability (HECC) Project; and 3 percent to administration. Balance requires sufficient support for Earth science research and analysis to effectively develop and utilize the space-based measurements. A balanced Earth science and applications program supports a robust community applying space-based measurements of Earth to benefit society for a broad range of purposes including research, forecasting, public safety, and business.

Balance of Responsibilities to Partner Agencies

NASA ESD has a variety of responsibilities to other agencies. Three core responsibilities are listed here:

- *NOAA Operational Satellite Development.* NASA Goddard Space Flight Center (GSFC) has responsibility for developing and procuring satellites for NOAA NESDIS, under direct agreement between NOAA and GSFC going back many years. This is not included within the ESD budget, and is not under ESD management authority. A separate NOAA partnership for the on-orbit Suomi National Polar-Orbiting Partnership (S-NPP) mission, initiated during the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) program, was carried within the NASA ESD development budget, although operations are now the responsibility of NOAA.
- *Sustainable Land Imaging (SLI).* NASA ESD has responsibility for developing and procuring the Landsat satellite series, under its SLI partnership with USGS. The budget for this partnership project is included within the ESD systematic mission budget line.

- *Satellite Needs Working Group (SNWG).* SNWG provides a means for multiple government agencies to provide input on national needs that could guide priorities for new NASA observations and ensure more effective applied use of current observations throughout the U.S. government.[9]

NASA's obligation to the first two of these is well-defined, with clear expectations and budget obligations. The third is quite flexible, with NASA given discretion as to whether and how needs from other agencies get reflected in ESD priorities. In general this SNWG process has proven both less burdensome to ESD and more beneficial to partner agencies than might be anticipated. The balance (between partner needs and ESD's own needs) achieved by ESD in each of these areas appears appropriate, in that those partner needs complement ESD's missions without being disruptive and do not dominate ESD budgets.

Balanced Applications to Society

NASA ESD measurements are critical to advancing understanding and prediction of the Earth system, which carry tremendous benefit to humanity. The science program at NASA ESD is designed to perform this function. In addition, space-based measurements of Earth can be applied more locally and in other ways to benefit communities and businesses. The Applications program at NASA ESD is designed to translate NASA Earth observations and science to the benefit of communities and businesses. In a balanced program, measurements of Earth from space are translated into human benefit.

Elements of a Balanced Flight Program

Beyond general programmatic balance, the ESD Flight program has additional balance issues that are critical to address (Box 4.6 provides an example of the trade-offs inherent in achieving balance):

Balance Between Large and Small Flight Missions

A mix of large, medium, and small flight missions will best advance progress in Earth remote sensing science at NASA. More expensive missions with more capable instruments or multiple instrument packages may be the best option for addressing certain critical science questions. Smaller, less expensive missions can address many science questions and provide more frequent opportunities to innovate and engage the science and engineering communities through a higher cadence of mission opportunities. Achieving the right balance among large, medium, and small flight missions is critical. Large missions cannot be allowed to consume too much of the budget and thereby stifle the innovation fostered by frequent opportunities for smaller, competed missions. Large missions, especially, should be cost constrained (NRC, 2012, p. 5).

Balance Among Technology Development Phases

Investments in innovation are critical to the success of this new program. Earth system science and applications rely on long-term (sustained) observations of many key aspects of the Earth system. Yet, there

[9] "The Satellite Needs Working Group (SNWG) was chartered as an interagency working group by action of the National Science and Technology Council (NSTC), Committee on Environment, Natural Resources, and Sustainability (CENRS), U.S. Group on Earth Observations (USGEO) Subcommittee. The SNWG supports an annual Satellite Needs process by which federal departments and agencies can communicate their Earth observation satellite measurement or product needs to NASA and other providers of satellite observations. The SNWG federal high-priority satellite needs collection was initiated in response to the President's Budget for Fiscal Year 2016, which reflects the decision to make NASA responsible for the acquisition of the space segment for all U.S. government-owned civilian Earth-observing satellites except National Oceanic and Atmospheric Administration (NOAA) weather and space weather satellites. The Administration further recognized that user agencies will continue to need satellite data from NASA, and that their needs should serve as input to NASA decisions on which measurements to transition from experimental to sustained observations." From "USGEO Satellite Needs Working Group Reporting Federal High-Priority Satellite Needs," available at https://remotesensing.usgs.gov/rca-eo/documents/Satellite_Needs_Collection_Survey.pdf.

BOX 4.6 ACHIEVING BALANCE IN FLIGHT PROGRAMS: PERFORMANCE, COST, AND RISK

A healthy Earth science flight program requires careful consideration of the appropriate balance between the three interrelated parameters of performance, cost, and risk. Increasing performance (i.e., through increasing scope or tightening technical requirements) generally implies an increase in cost or risk. Costs can be lowered by accepting more risk or reducing performance (e.g., by relaxing technical requirements or reducing the scope of a mission). Similarly, low tolerance to risk can increase costs as funding is expended to, for example, improve parts selection, complete additional analyses, and hold in-depth reviews.

Which of the three parameters are actively managed versus allowed to vary as a function of the others has program-wide implications. Low tolerance to risk coupled with tight technical requirements results in higher mission costs, which can limit the scope of the overall program as the number of missions implemented decreases in response to the increase in individual mission costs. Acceptance of high levels of risk may lower a mission's cost, but it may also result in increased incidences of mission failures or shorter mission lifetimes. The program-level requirement for a mission's success or its ability to tolerate reduced performance or limited mission duration should be used to determine its appropriate risk posture for a given mission. Higher levels of risk are expected to be acceptable, for example, within the Venture Program than in the Designated program element.

ESAS 2017's recommended program includes a variety of program elements that serve to enable active consideration of the balance between cost, performance, and risk while providing flexibility throughout the decade to evolve as new opportunities emerge, technologies are developed, scientific discoveries are made, and the international contributions to the Program of Record evolve.

is at present no mechanism to fund early-stage innovation that might lead to lowering the cost of providing for long-term observations. Instead, teams are currently incentivized to improve upon state-of-the-art to qualify for consideration in competitive funding solicitations that are targeted to new scientific investigations. Put simply, there is no incentive to drive for efficiency. The committee therefore proposes that ESTO establish a competitive call to incentivize development of game-changing technologies to lower the cost and risk associated with provision of sustained observations needed for Earth system science. The ESTO budget is currently at the low end of its historical range as a percentage of ESD's budget. The committee recommends (Recommendation 4.6) that the ESTO budget be increased to 5 percent of the ESD budget, which remains within the historical range of ESTO funding (Table 4.2).[10]

Balance of Mission-Enabling Investments versus Flight Missions

NASA must balance its Earth science technology efforts across broadly based investments that reduce cost across multiple programs and focused mission technologies. In particular, broadly based investments that reduce the cost or improve the resiliency of space launch are critical (including small launch vehicles, standard bus architectures, and secondary payload and rideshare approaches). NASA also has the critical role of continuing to advance Earth system science sensor technology. As the Earth science community works to improve the accuracy of its measurement and prediction capabilities and translate this knowledge into applications that impact U.S. economic competitiveness, national security, and quality of life, NASA must continue to keep the Earth science sensor community at the cutting-edge. As a means to provide this

[10]As noted in Chapter 3, a portion of the Incubation program's budget is expected to flow to the Earth Science Technology Office (ESTO) commensurate with its role in the maturation of instrument and technology concepts. The remaining funding to support the recommended increase in ESTO's budget is obtained through decreases in other program elements consistent with the report's recommendation to maintain those other program elements within their historical funding ranges.

balance, new technology funds are included in the coming decade for both broadly based investments and focused technology investments through the Incubation program element. In addition to focused technology investments for priority instruments and missions, this program element also includes an Innovation Fund to enable program-level response to unexpected opportunities that occur on subdecadal scales.

Balance Between Heritage Technology and New Technology

The development of advanced technology can provide novel measurement capabilities and the ability to make needed measurements at reduced cost. Less expensive measurement technologies are critically important if NASA ESD is to innovate to obtain the most critical measurements within its expected budget. In a balanced program, new technology is continuously introduced into space-based measurements, and innovation to improve existing measurements and measure new variables of importance is implemented. New technologies do require investment, however, and their successful adoption requires demonstrated capabilities to achieve measurement objectives. In the meantime, heritage technologies are essential for the achievement of observation objectives until such time as reliable transition to new capabilities can be accomplished.

Balance Between Extended Operations and New Missions

Valuable data can be collected from missions that remain functional beyond their designed lifetime, but this data collection requires resources that might be used for other purposes. Extending the operational phase of successful space missions beyond their design lifetime generally provides valuable data at a low cost, relative to new instruments and launches. The recent NASEM (2016a) report (*Extending Science—NASA's Space Science Mission Extensions and the Senior Review Process*) states that the present method of "senior review" to evaluate mission extensions is working well.

Balance Between Continuity of Existing and Novel Measurements

Some satellite data records have been established for which continuation (continuity) of the record in time carries significant scientific and practical benefits (Box 4.7). Achieving the appropriate balance between investments to maintain continuity versus the development of new measurement capabilities is a longstanding challenge,[11] one that is complicated further when the line between a continuity measurement and a novel measurement is blurred. For example, this survey's recommended Surface Deformation Targeted Observable could be justified on the basis of continuity, extending the record to be initiated by NISAR. However, this Targeted Observable's new emphasis on temporal versus spatial resolution implies some novelty to address needs for both continuity and new measurements, so it is hard to make a clear distinction.

The committee emphasizes that many continuity measurements are provided by the national and international Program of Record (POR), especially the European Copernicus, perhaps making the proposed set of measurements appear skewed toward new measurements. However, if those POR measurement continuity capabilities did not exist, the proposed measurements recommended by the committee would have involved a different mix.

Execution of the national and international POR and the recommendations of this decadal survey, taken together, will provide for the continuation of many key satellite records through most of the next decade. The planning and preparation to continue such measurements beyond the next decade is urgently needed. International collaboration is required to ensure continuity, given individual agency resource constraints. The recent agreement between NASA, NOAA, ESA, EUMETSAT, and the European Union (via its Copernicus

[11] A recent report from the National Academies of Sciences, Engineering, and Medicine (NASEM, 2015) sought to establish a more quantitative understanding of the need for measurement continuity and the consequences of measurement gaps.

BOX 4.7 THE NEED FOR CONTINUOUS MEASUREMENTS

Satellite remote sensing of Earth grew rapidly in the 1970s, and many measurements became indispensable for Earth science and applications and are continuing. These measurements are used both for immediate applications and to establish long-term records that are essential for understanding Earth system behavior on longer time scales. A 2015 report of the National Academies of Sciences, Engineering, and Medicine (NASEM, 2015) identifies key evaluation factors and puts forward a decision-making framework that quantifies the need for measurement continuity and the consequences of measurement gaps for achieving long-term science goals. It is important for Earth science and applications that these measurements be improved and continued, including observations that meet climate quality standards.

A partial list of key variables for which continuity of measurement is important is provided in Table 4.7.1. Table 4.7.1 is not a complete list of all relevant measurements and it is not a priority listing. The committee has assessed the likely continuity of these and other measurements through the end of the coming decade, based upon the Program of Record (POR) (Appendix A) and the Observing System Priorities table (Table 3.4), to identify potential gaps as it developed its recommended program.

Two Targeted Observables (Mass Change and Surface Deformation and Change) are included in the Designated program element specifically to ensure continuity; several of the Targeted Observables listed in Table 3.6 (Greenhouse Gases, Ozone and Trace Gases, and others) are recommended for competition in the Earth System Explorer program element in part to provide continuity; and others may be addressed via the recommended Venture-Continuity competition strand described in Chapter 3. The provision of continuous measurements of such critical variables by the international community, which allowed the committee to focus its attention on new or missing observations, underscores the importance of the POR as the foundation upon which the committee's recommendations were established. If the POR and the program priorities recommended here are executed as planned by NASA, NOAA, USGS, and our international partners, then it is likely that many (but not all) of these critical records will continue to be available for science and applications in the United States.

TABLE 4.7.1 Examples of Observations Associated with Potential Continuity Needs

Observation	Purpose	Start of Record	Description
Land-Surface Conditions	Monitor land-surface conditions.	1972—Landsat I	Global visible and IR imaging of land at high spatial resolution.
Ocean Color	Measure near-surface ocean color for fisheries and ocean biology and chemistry.	1978—CZCS	Multiwavelength visible imager.
Sea-Ice Concentration	Important for navigation, fisheries and climate monitoring.	1978—Nimbus 7 SMMR	Multiwavelength microwave imager.
Precipitation	Microwave imager provides estimate of precipitation over ocean.	1978—SMMR 1997—TRMM radar	Multiwavelength microwave imager. Precipitation radar.
Temperature and Humidity Profiles	Needed for weather forecasting and measuring change.	1978—Microwave and thermal IR sounding begins	Thermal IR and microwave sounders for all-weather data.
Ocean Vector Winds	Useful for weather forecasting and seasonal prediction.	1978—Seasat, *but record not continuous*	Radar scatterometry or polarimetric microwave radiometry.
Cloud Cover and Optical Properties	Cloudiness is a key weather variable, and clouds are also a key climate variable.	1978—AVHRR; geostationary imaging	Multiwavelength visible and IR imaging.

BOX 4.7 Continued

Observation	Purpose	Start of Record	Description
Solar Irradiance	Total solar irradiance is the energy source for Earth; the ultraviolet radiance influences stratospheric ozone.	1979—Nimbus 7 ERB 2003—SORCE	Total irradiance from the Sun. Total and spectral irradiance from the Sun.
Earth Radiation Budget	Measures changes associated with clouds, temperature trends, or volcanic eruptions.	1979—Nimbus 7 ERB	Absolutely Calibrated Broadband solar and terrestrial radiance at the top of the atmosphere.
Ozone and Trace Gases	Reactive chemicals affect UV radiation, air quality, and climate.	1979—SAGE I, Nimbus 7, TOMS, SBUV 1995—GOME	Solar backscatter, solar occultation, thermal IR, and microwave sounding.
Aerosol Optical Depth	Aerosols affect air quality, weather, and climate.	1999—MODIS, MISR	Solar backscatter.
Sea-Surface Temperature	Needed for weather forecasting and monitoring ocean change.	1981—AVHRR on NOAA-7	Thermal infrared and microwave imaging.
Vegetation Greenness Index	Estimation of the photosynthetic activity indicates health and productivity of land vegetation.	1981—AVHRR NDVI	Multiwavelength reflected solar imager.
Sea-Surface Height	Global measurements of sea-surface height are useful for quantifying sea-level rise, diagnosis and forecasting of El Niño, and determining ocean heat storage.	1992—TOPEX and JASON	Radar altimetry.
Mass Change	Gravity measurements can be used to monitor ocean mass, land-surface total water storage, and land-ice mass changes.	2002—GRACE	Spatial and temporal anomalies of gravity field.
Ice Elevation	Changes in land-ice volume are an important potential source of large sea-level changes.	2003—ICESat	Laser altimetry.
Cloud/Aerosol Vertical Profiles	The vertical structures and properties of cloud and aerosol layers are important for weather and climate.	2006—CloudSat 2006—Calipso	Radar and lidar profiling of cloud and aerosol structure.
Greenhouse Gases (CO_2, Methane)	Important in understanding the factors controlling carbon fluxes and atmospheric concentrations.	2009—GOSAT 2014—OCO-2 2002—SCIAMACHY	Reflected solar spectrometer.

NOTE: Not in any priority order. These examples, and others not included in this sample, should undergo formal review, as described in the report *Continuity of NASA Earth Observations from Space: A Value Framework* (NASEM, 2015), to plan for continuity needs.

program) to continue high-precision ocean altimetry measurements via the Sentinel-6 program provides an example of international collaboration. As noted in Recommendation 2.2, NASA should continue to work with international partners to develop an international strategy for maintaining key satellite measurements and establish data-sharing agreements among the nations making the measurements.

Finding 4.5: Maximizing the success of NASA's Earth science program requires balanced investments across its program elements, each critically important to the overall program. The *flight* program provides observations that the *research and analysis* program draws on to perform scientific exploration, the *applied sciences* program transforms the science into real-world benefits, and the *technology* program accelerates the inclusion of technology advances in flight programs. The current balance across these four program elements is largely appropriate, enabling a robust and resilient Earth science program, and can be effectively maintained using decision rules such as recommended in this report. Some adjustment of balance within each program element is warranted, as recommended in this report.

Recommendation 4.6: NASA ESD should employ the following guidelines for maintaining programmatic balance:

- ***Decision Rules.* Needed adjustments to balance should be made using the decision rules included in this report.**
- ***Flight versus Nonflight.* Flight programs should be approximately 50-60 percent of the budget.**
- **Within Nonflight:**
  - —***R&A Program.* Maintain at its current level of the ESD budget.**
  - —***Technology Program.* Increase from its current level of 3 percent to 5 percent of the ESD budget.**
  - —***Applications Program.* Maintain at its current level of the ESD budget.**
- **Within Flight:**
  - —***Program Elements.* Ensure that no flight program element is compromised by overruns in any other element.**
  - —***New versus Extended Missions.* Continue to use the present method of "senior review," consistent with guidance from the National Academies of Sciences, Engineering, and Medicine (NASEM, 2016a).**
  - —***New Measurements versus Data Continuity.* Lead development of a more formal continuity decision process (as in NASEM, 2015) to determine which satellite measurements have the highest priority for continuation, then work with U.S. and international partners to develop an international strategy for obtaining and sharing those measurements.**
  - —***Mission-Enabling Investments versus Focused Missions.* Other than additional investments in the Technology program and the new Incubation program element, no change in balance is recommended.**

Scope Within Nonflight Program

As noted throughout this section, NASA's nonflight programs are essential to its overall mission. These programs are performing well and are all in approximately correct balance at the current time. Two small scope adjustments are recommended:

Recommendation 4.7: NASA should make the following scope changes to its program elements:

- ***Technology Program.* Establish a mechanism for maturation of key technologies that reduce the cost of continuity measurements.**

- ***Applications Program.*** **Redirect a small portion to new funding opportunities that focus specifically on taking early-stage ideas and exploring how to move them into applications, including co-sponsorship with NOAA and USGS.**

Balance and Scope Within the Venture Program

The Earth Venture Program was established to "create space-based observing opportunities aimed at fostering new science leaders and revolutionary ideas" (NRC, 2007). To achieve this, NASA implemented three strands of Earth Venture elements. The first is the Earth Venture Mission (EV-M) opportunity, which solicits stand-alone space missions with a cap of $150 million. The second is the Earth Venture-Instrument (EV-I) opportunity, which solicits instrumentation for which NASA assumes the responsibility of identifying a launch opportunity. EV-I is solicited at approximately 18 month intervals. Last, the Earth Venture Suborbital (EV-S) opportunity solicits suborbital studies with an approximately 4-year cadence, selecting approximately five investigations per cycle, cost-capped at $30 million each, lasting 5 years each. Through the implementation of this program, NASA has provided two opportunities in the past decade for missions, six for instrumentation, and two for suborbital proposals.[12] The result has been that the program has succeeded in fostering innovation and stimulating a vibrant Earth science community through the provision of multiple opportunities for large-scale observation capabilities.

Even though the Earth Venture program was initiated nearly a decade ago, only one EV-M has been launched (CYGNSS), none of the EV-I missions has been flown yet, and one cycle of the EV-S has been completed. As a result, the relative benefits of these programs are still not fully understood. The committee fully supports the continuation of the Earth Venture program in its present form, but after several of the EV-I missions and the contributions from Cyclone Global Navigation Satellite System—Earth Venture Mission (CYGNSS) are better understood, a cost-benefit analysis of the EV investments would help inform the amount and distribution of future investments in the program.

Finding 4.6: The Earth Venture program has provided increased opportunities for innovation in scientific Earth observations. However, it is too early in the program, with too little history, to assess the benefits of modifying the present three-strand Venture structure or adjusting cost caps beyond the recommended addition of a Venture-Continuity strand.

Recommendation 4.8: The Midterm Assessment, with a longer program history than is available to ESAS 2017, should examine the value of each Venture strand and determine whether the cadence or number of selections of any strand should be modified. In particular, the Venture-Suborbital strand should be compared to the approach of executing comparable campaigns through the research and analysis program to assess which approach serves the community better.

Budget Guidance and Decision Rules for Maintaining Balance

The committee's suggested decision rules have two components. First are guidelines for how to allocate funding that becomes available as current flight missions are completed (referred to as the "funding wedge"). Second are guidelines for ensuring various aspects of balance in the program's overall budget. The assumption, used throughout this report, is that future budgets correspond to the FY 2016 budget adjusted for inflation. Computation of the funding wedge is described in detail in Chapter 3. The conclu-

[12] Information on NASA's Venture-class program can be found at https://essp.nasa.gov/projects/.

sion was that the cost to complete the POR (the NASA-baseline missions already "in implementation") was estimated to be $3.6 billion and the "funding wedge" for new missions advocated in this report was estimated to be $3.4 billion.

Overall Program Balance

To maintain program balance, the committee recommends (Recommendation 4.6) that ESD budget components should be approximately consistent with historical budgets. For the entire ESD budget, the following guidelines are recommended.

- *Earth Science research* should be maintained at approximately 24 percent of the budget (within the range 22-26 percent). (This value of 24 percent includes 18 percent for openly competed research and analysis, and approximately 3 percent each for computing and administration.)
- *The Applications program* should be maintained at 2-3 percent of the budget.
- *The Technology program* should be increased from its current 3 percent to about 5 percent.
- *Flight programs,* including Venture, should be 50-60 percent of the budget.
- *Mission operations* should be 8-12 percent of the budget.

Allocation of the Funding Wedge Within Flight

As general guidance for allocating the funding wedge within flight programs, an appropriate distribution of the ESD investment is 35-45 percent in large missions, 40-50 percent in medium and small missions, and 10-15 percent in technology-related aspects of flight development. No single mission should consume more than 25 percent of the funding wedge.

Managing Budgets

Decision rules are most effective when budgets are managed carefully across ESD. Mission development, with its large costs and uncertainties, traditionally results in significant budget management challenges. Recommendation 3.3 provides specific guidance concerning the cost-aware management of missions in development.

Decision Rules for Budget Changes

The committee expects that budgets will be different from the nominal assumptions made in accordance with the committee's statement of task. A critical purpose of decision rules is to maintain the scientific and technical capacity for a robust space-based Earth science program when budgets change. Maintaining capacity is important, since that capacity takes a long time to build (in some cases, longer than the mission development time scale) and is easily disrupted.

The committee places the highest priority on continuity of critical missions, followed by competitive opportunities in the Earth System Explorer and Earth Venture lines, followed by the large missions. However, because the highest overarching priority is a balanced portfolio, it is important that no one aspect of the portfolio be reduced excessively, to keep others intact.

As a result, in managing potential *budget reductions* that impact the scope or cadence of the new measurements of this decadal survey:

- Reductions should first be accommodated by delaying the large missions.
- If additional reductions are required, the medium-size Designated missions should be delayed, unless these delays threaten the continuity of data sets that require continuous measurement.